CRWR Online Report 10-10

The Role of Aquifer Storage and Recovery (ASR) technique in Sustainability: a case study for Kuwait

by

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December 2010

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By

Duaij AlRukaibi, B.Civil.E.

Thesis

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science in Engineering

The University of Texas at Austin

December 2010

Dedication

Dedicated to my parents who helped me in

Becoming in what I am right now. I hope this work

Satisfy their expectation of me. They have been a great support for me in my entire

career.

Acknowledgements

I would like to thank my supervisor, Dr. Daene McKinney, for his guidance and support; it has been a privilege to work with him. My sincere gratitude is also goes to Dr. David Maidment for his the technical supports he offered. It has been a privilege to work with such brilliant and wonderful advisors. I'm also thankful to Dr. Naji Almutairi (General Manager of KISR) and Dr. Khaled Hadi for their help and providing me all of the data related to groundwater of Kuwait, and authorizing me to use the data in this research. It would not have been possible to acquired field data without them.

.My gratitude also extended to the following People who provided me with information and Assistance. Dr. Hamdy Aljmeely, Mr. Amit, Fahad Alfadhli, Nawaf AlHajri, and Talal Alotabi. A special thanks goes to my brother Abdulaziz AlRukaibi and my cousin Mohammed AlRukaibi for their help.

Finally, a special thanks to the government of Kuwait for giving me the opportunity to pursue my graduate study at the University of Texas at Austin. I am most thankful to my family for their support and patience.

Duaij AlRukaibi

December 03, 2010

Abstract

The Role of Aquifer Storage and Recovery (ASR) technique in Sustainability: a case study for Kuwait

Duaij AlRukaibi, M.S.E.

The University of Texas at Austin, 2010

Supervisor: Daene McKinney

Abstract

Kuwait is an arid country situated at the head of the Arabian Gulf and its water resources can be classified into three significant types: (1) natural (groundwater) and (2) artificial (desalinated sea water and treated wastewater). In the absence of surface water bodies, groundwater constitutes the most important natural water resource in Kuwait with TDS ≤10000 mg/L in central and south Kuwait. Only in the north can one find fresh water lenses. Brackish groundwater are used for irrigation, landscaping, construction work, non-potable use in households and mixing with desalinated water up to 10%, to make it potable. The occurrence of usable groundwater is limited to the Kuwait Group and Dammam Formation. Due to over-pumping of groundwater over the last few years, the levels and quality of groundwater are deteriorating. Kuwait is described as the poorest country in terms of water availability (UN World Water-2003). The current rates of water

consumption are very high, with 459.6 L/C/d and almost 91 L/C/d for fresh and brackish water, respectively. The water budget of the water resources, represented as percentages is 59% from desalination sea water plants, 32% from groundwater with the possibility to increase the use of this resource and 9% from waste water reuse plants. Although Kuwait does not have any surface water, but it depends on technology to produce water recourses to meet the demand. The best solution for solve the issues of declining water levels and increasing salinity is artificial recharge. Artificial recharge has been applied in Kuwait in different groundwater fields since the 1980s. In addition, the available surface storage capacity of 11.7 Mm^3 freshwater is sufficient to meet demand for about 7 days. So, Aquifer storage and recovery (ASR) can be used to store the water in aquifers instead of surface storage. ASR entails storing water in aquifers during wet times and recovering the water from the same well during drought times. Surface storage needs construction resources and vast land. In contrast, storing water in aquifer storage does not need that and it can decrease salinity and keep the water table constant. The water availability for artificial recharge can come from desalination and wastewater plant. The capacity and production of desalination plants are 1.425Mm^3/day (525.125Mm^3/yr) and 1.31Mm^3/day (478.15 Mm^3/yr), respectively from 5 stations. The excess capacity is 115000 m^3 per day and could reach 290000 m^3 per day in the winter season. Wastewater treatment plants produce from 3 plants around 0.337 Mm^3/day (123.342 Mm^3/yr) and the newest plant (operating by RO system) produces 0.32 Mm^3/day (117.12 Mm^3/yr) and will reach 0.643 Mm^3/day (235.338 Mm^3/yr) in 2015. The water produced from wastewater treatment plants has good quality and can be used for irrigation, greening enhancement, landscaping, recreation (artificial river and lakes) and artificial recharge. Also, using water treated for artificial recharge will improve the quality of injected water that has been successfully treated with soil aquifer treatment technology. Groundwater pumping is 200 Mm^3 annually and is likely to reach 280 Mm^3 in the future. This research will explore and create a database for water resource by GIS software using its tool to select and display suitable areas for ASR operation. Artificial recharge in Kuwait has used the concept of injection and recovery of water in one cycle, while here we will apply the multi-cycle concept to avoid increasing the piezometric head and clogging the porous media. The injected water will be from wastewater treatment plants with a TDS content of less 500 ppm and the TDS of recovered water in each well less than 1500 ppm. Moreover, there are criteria for selecting a domain for artificial recharge, for example, moderate transmissivity, The TDS of the aquifer should not exceed 5000 ppm, and the horizontal and vertical hydraulic gradient should be as small as possible and close to the stations suppler and demand center. The success of artificial recharge will depend on the recovery efficiency (RE) in every cycle which will increase if artificial recharge done in the correct way. The RE increases with a decrease in time between the stopping of injection and the starting of the recovery operation. Aquifer storage and recovery can play an important role as sustainability tool to resolve water resource problems, improving water quality, better than surface water storage since it minimizes construction of new infrastructure and uses that cost to initiate new desalination or waste water plants. At the end of this research we will have demonstrated the concept of the process of ASR including the volume and time for injection and recovery of water in multi-cycles and in different suitable sites.

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CHAPTER 1: Introduction

The planning and management in Civil engineering measures the demands of local and global society and finds optimum alternative solutions to supply them by different methods and policies. Water resources and environmental engineering is one of branch of Civil engineering that deals with prediction, management and planning of the quantity and quality of water in the surface (lakes, rivers and seas) and subsurface (aquifer) systems. Natural resources planners and managers are concerned with two parameters that, supply and demand, within specific regions. Also, they develop and integrate the natural resources and try to make them continuous in supply by applying different methods and techniques. A significant increase is expected in water demand during the next few decades based on the population growth all over the world and increasing environmental pollution will contribute to poor quality of available water resources. These will push decision makers to find alternative solutions for the supply in normal and critical times.

Climate change will put pressure and indirect impact on groundwater by decreasing water availability, degrading water quality and increased drought events from increasing temperature in arid regions. Groundwater is more difficult to study than surface water since it is more ambiguous and needs more gauge stations to collect temporal and spatial data at depth. Groundwater issues are emerging worldwide and leading water resources engineers and managers to find sustainable water resource tools for the declining ground water levels, salt water intrusion, steadily decreasing river flows, deteriorating ground water quality, and land subsidence. Due to population growth and non-sustainable tools for domestic, agricultural and industrial development, a significant increase in water demand. In addition, increasing environmental pollution in the world contributes to low quality and overdraft of groundwater resources.

Storing large volumes of water in the subsurface is increasingly recognized as a cost-effective and environmentally desirable and sustainable option. To overcome the above-mentioned problems, the water resources researchers, engineers and managers created a technique that can be used to artificially recharge groundwater reservoirs. Artificial recharge of water is a tool for sustainable water resources management where water is added (injected) to a groundwater body to make it available for later use at time of need or emergency conditions. It is increasingly being practiced as a water management tool worldwide to manage and control available water resources in an efficient manner. The water to be recharged can be clean water (water overflow, storm water, surface water), brackish water or treated water. Not only can water be stored in the subsurface in times of surplus for use in times of shortage, it can be used to obtain other goals and control other water-related problems such as land subsidence, climate change impacts and earth fissure development.

1.1 background of artificial recharge

Artificial recharge is the method whereby surface water is transferred to the subsurface to be stored in an aquifer. The common methods and techniques that have been used and implemented are injecting water into wells and transferring or recharge water into spreading basins where it allowed to infiltrates into the subsurface. The first steps in artificial recharge in both techniques have had technical constrains that have limited their common implementation. Injection water through wells works under specific conditions, for instance if the aquifer is confined or semi confined and overall the evaporation rate is high (arid or semi arid region). Recharge basins are the simplest, oldest and most widely applied method of artificial recharge requiring a shallow ground water level, less than 40 meter, in an unconfined aquifer. The evaporation rate should be relatively low and recharge water quality should be similar to the water quality of the aquifer and a vast surface area is needed to implement the artificial recharge. With these conditions, water moves from the ground level to an unconfined aquifer by percolation through the porous soil.

Subsurface water storage for later use is an efficient way to store water because it is not vulnerable to evaporation losses and it is relatively safe from contamination. In this framework, it is a form of water conservation, in that water that is lost through evaporation and evapotranspiration from dams and rivers or from outflows to the sea (fresh or waste water), can be captured and made available for later use. The numerical modeling can be used to evaluate and analyze the result of injecting water with respect to the water level, water quality and movement of water in the aquifer. The major techniques used for artificial recharge of injected and transferred water to aquifer are explained below in details.

Table 1 Definitions of types of Artificial Recharge (Dillon, 2005)

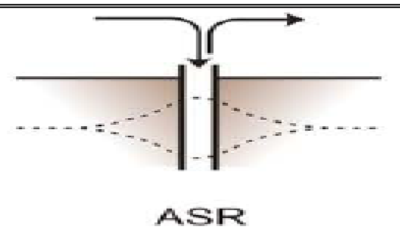
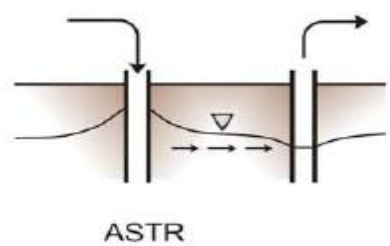
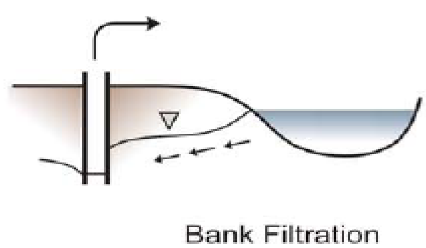
Types of artificial recharge	**Schematic of aquifer recharge**
Aquifer storage and recovery (ASR) injection of water into wells for storage and recovery from the same wells.	
Aquifer storage transfer and recovery (ASTR) it is the same concept of ASR while the recovery done from a different borehole, that provide more water treatment	
Bank filtration, extraction of groundwater from a well near or under a river or lake to induce and bring infiltration from the surface water in that way improving and making more high quality of water recovered.	

Table 1 (Continued)

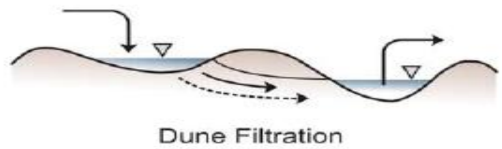
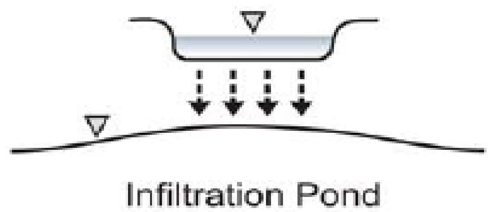
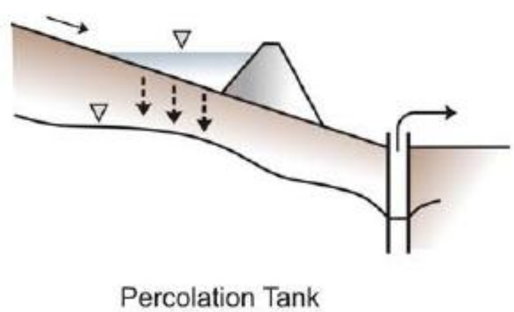
Dune filtration, infiltration of water from ponds or lake constructed in dunes and pump out from wells or ponds that at lower elevation for water quality improvement.	
Infiltration ponds, ponds constructed usually off-stream where surface water is diverted and allowed to infiltrate (generally through an unsaturated zone for more treatment) to the underlying unconfined aquifer.	
Percolation tanks, a term used commonly in India to describe harvesting of water in storages built in temporary streams where water is held and infiltrates through the base to increase storage in unconfined aquifers and is extracted down the valley.	

Table 1 (Continued)

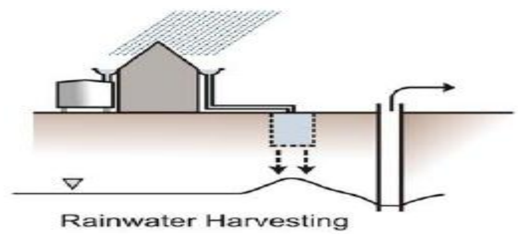
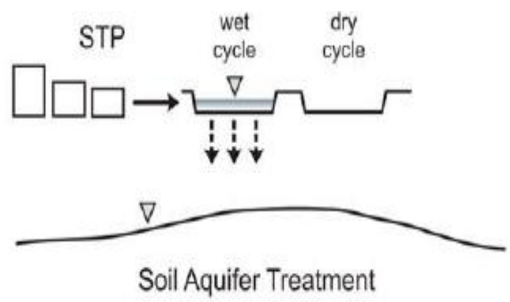
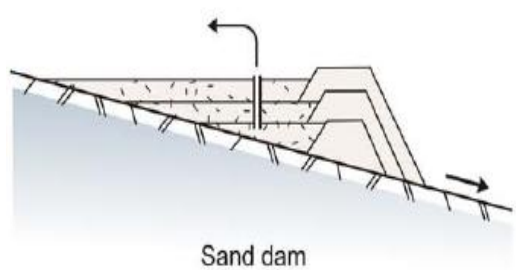
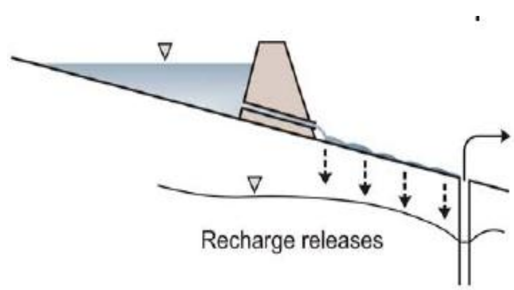
Rainwater harvesting, a tank connected into a borehole, well or a caisson filled with sand or gravel and allowed to get into to the water-table where it is collected by pumping from a well.	
Soil aquifer treatment (SAT) treated sewage effluent, known as reclaimed water, is infiltrated through infiltration ponds to facilitate nutrient and pathogen removal in passage through the unsaturated layer for recovery by boreholes after residence in the aquifer.	
Sand dams, built in temporary streams in arid region on low permeability lithology, these fence in sediment when flow occurs, and following successive floods, the sand dam is raised to create an "aquifer" which can be tapped by boreholes in dry seasons.	

Table 1 (Continued)

Underground dams, in temporary streams where basement highs constrict flows, a trench is constructed across the streambed keyed to the basement and backfilled with low permeability material to help retain flood flows in saturated alluvium for stock and domestic use.	
Recharge releases, dams on temporary streams are used to hold flood water and uses may include slow release of water into the streambed downstream to match the capacity for infiltration into underlying aquifers, thereby significantly enhancing recharge.	

1.2 Aquifer Storage and Recovery (ASR)

Aquifer Storage and Recovery (ASR) is an innovative water management approach particularly suitable for those areas with seasonal variations in water demand and supply, being used to optimize available water resources and decrease adverse effects of overdraft. In addition, ASR is a method of improving water supply reliability and water quality by controlling a groundwater basin or aquifer as subsurface storage. It basically functions as a water bank and it provides a guaranteed water supply in the future if one of the water resources is depleted. In the engineering view, if the aquifer is the only main natural water resource in a semi-arid or arid region and it is affected by overdraft in the time of demand then it needs to receive water to improve the quality and keep the water level in the time water is available. ASR injects high quality water through ASR wells and stores it in a suitable aquifer during winter months when demands are low and the water is available for later use in the same way as stored water in a surface storage or tank. So, this technique involves injection high quality water from captured surface water runoff or treated wastewater.

Recovery is the next step of the ASR process, which depends on the division of the storage into seasonal, long-term “bank water”, emergency and diurnal storage. Recovery efficiency describes the ratio of the water recovered from the aquifer to the volume injected into the aquifer. The potablility of recovered ASR water depends on the concentration of TDS resulting from the merging of the injected and native water. The TDS of the recovered water should meet TDS standards specified by the World Health Organization (WHO). Water injected into an aquifer displaces native groundwater and creates what is conceptually called a bubble zone of better quality water that can be pumped out at a later time. A successful ASR system requires a proper aquifer (e.g., basalt, sand and gravels, etc.) to store the water and a source of water, such as a river, lake, treated wastewater, in wintertime, or even water from another aquifer. Other key components for establishing the ASR are supporting infrastructure such as the latest effective well technology and an available energy supply to operating them. Moreover, the source water and native groundwater must be compatible in order to avoid any plugging. This is the most important factor to the success of an ASR technique. ASR is a function of pumping water in and then out of an aquifer with or without a time gap between them. It relies on the type of subsurface storage and the mixing of injected water with groundwater will result in some benefits for the subsurface or groundwater and perhaps some concern and risk that should be considered.

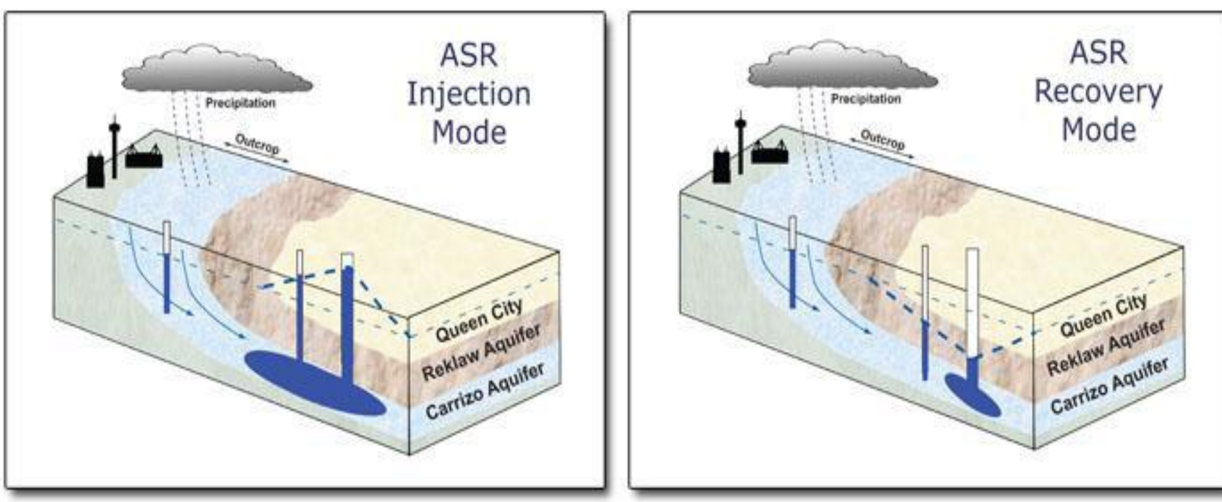


Figure 1 ASR in injection and recovery phase (Citation: www.usgs.gov)

The types of subsurface storage that are used as a water bank to implement ASR technique are based on when the recovery phase will occur.

Seasonal storage - First, seasonal storage is used to store the injected water during winter time and then it is recovered during summer time. This is most often used when the dry-season demand is almost the same as the wet-season supply.

Long-term storage - The second type of subsurface storage is long-term storage where water is stored during winter time, or during years when surplus water is available and it is recovered during dry years or when the capacity of other water sources is insufficient to meet demands. Long term storage not only provides protection against drought conditions, but it also provides security against future uncertainty in water supply due to climate change, environmental pollution and it restores the depressed water levels due to over exploitation. Water is stored to provide an emergency supply or strategic option when the main source of supply is unavailable or out of commission is called emergency storage.

Diurnal storage - The last type of subsurface storage is diurnal storage which works on a daily basis. During the first period of the day demands exceed supply capacity, then to recover the demands for the rest of the day by this storage. The storage requirements depend on supply, demands and water quality. From these the injection volume can be estimated in order to have a higher volume in the recovery phase. The subsurface storage is the sum of the required recovery volume and the buffer zone volume that lies between the injected water and native water in the aquifer.

The target storage volume (TSV) is an estimated of volume of water needed for the storage zone and buffer zone which is assisted to reach the optimum percentage of recovery efficiency. The volume of TSV is depended on more than one parameters such as thickness of the aquifer, hydraulic characteristics, transmissivity, vertical confinement, effective porosity and water quality (Pyne, 2005).

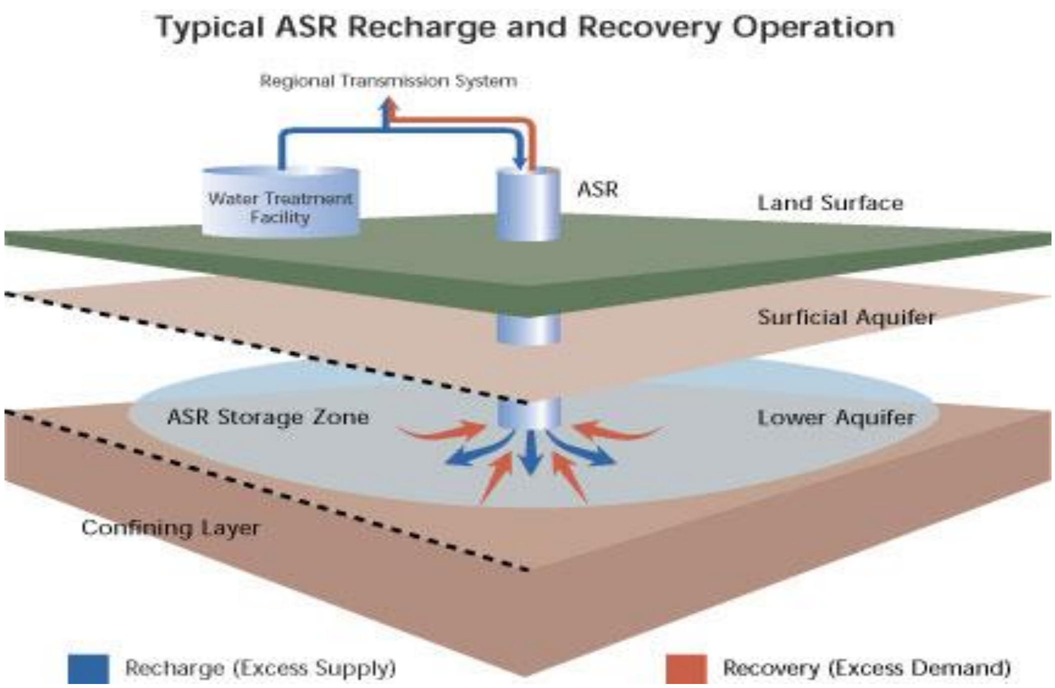


Figure 2 Typical ASR recharge and recovery operation (*Citation:* <u>*www.regionalwater.org/*</u>)

The benefits of ASR are divided into improving the water quality, physical management of the aquifer and reducing the impact of over-exploitation. Seawater intrusion and pollution have been identified as the primary factors for water quality degradation which when higher quality water is injected into the aquifer will provide a barrier and restrict the movement of seawater. Injection can mitigate land subsidence that results from pumping groundwater in surplus of natural recharge. The injected water fills any pore spaces and can create “hydrostatic pressure” among the rock particles and also can restore native groundwater levels that drop due to over-exploitation. As water is removed from these pore spaces by groundwater pumping, the level of the water table begins to drop and the land surface begins to lower, or subside. Through artificial recharge, it is possible to abstract water at higher rates during peak demand months than the long-term sustainable yield of the aquifer. Typically, groundwater has good quality due to protection from the overlying soil layer. There is also an ecological benefit such as a decrease the abstraction from natural surface sources, such as rivers and springs. Wastewater treatment plants produce high volumes of effluent water and less than the half of this effluent is used while the rest is discharged to the sea or rivers. An ASR system can store treated wastewater for later use. Many ASR systems utilize saline aquifers that were not considered beneficial and feasible before. Fresh water is created in a bubble zone around the injection well due to the different in TDS concentration between the saline aquifer and the injected water.

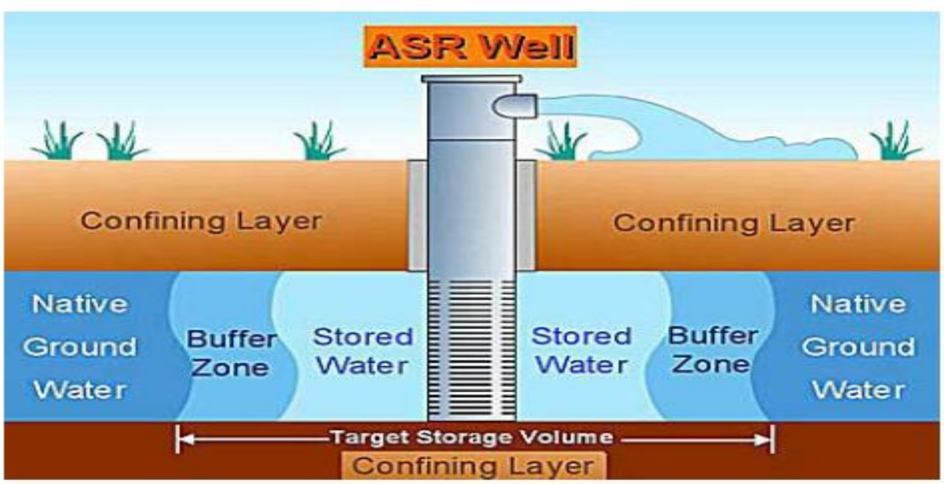


Figure 3 Target Storage Volume (http://www.asrforum.com/)

1.3 Case study: Kuwait

1.3.1 Background

Kuwait, one of GCC countries (Bahrain, Kingdom of Saudi Arabia, Qatar, Kuwait, United Arab Emirates and Oman), is located in the north western portion of the Arabian Gulf where it covers an area of 17818 km^2 and has a total coastline of 499 Km. Its geographic coordinates are (29º30' N, 45º45' E) and it shares borders with Iraq on the north and northwest and The Kingdom of Saudi Arabia on the south and southwest, and the Arabian Gulf bounds Kuwait on the east. There are nine islands in the country's territorial waters: Warbah, Bubiyan, Maskan, Failaka, Awhah, Umm Al–Naml, Kubbar, Qaruh, and Umm Al–Maradim. Bubiyan, the second largest island of the Arabian Gulf Island is composed of deltaic deposits from the Tigris and Euphrates river system. Failaka is lying 20 km northeast of Kuwait City at the mouth of Kuwait Bay, is thought by some to be the northernmost point of the Bronze Age civilization of Dilmun. There is also evidence that Failaka, referred to at the time as *Ikaros,* was settled by Greeks over two thousand years ago. The total population of Kuwait in 2009 is 3,484,881 which only 1,118,911 is Kuwaiti and the rest is foreign (obtained from the official website of the Public Authority for Civil Information). The weather is extremely hot in summer and cold in winter. The surface water drainage network is limited due to the arid climate and horizontal topography of Kuwait. Small wadis are developed in the shallow depressions in the desert terrain. They flow intermittently after intense rains. Kuwait depends mainly on crude oil reserves of about 104 billion barrels - about 8% of world reserves. The Gross Domestic Product (GDP) purchasing power is $151.3 billion while the GDP per capita is

$ 54260 and labor force is 2.091 million with non-Kuwaitis making up about 60% of the labor force (source: World Bank, world development indictors, 2008).

Kuwait is an arid country characterized by high temperature, low humidity and high evaporation with no surface water and only a small reserve of fresh groundwater in north. The summers in Kuwait are intensely hot and dry, with daily mean highs ranging from 40°C to 46°C, and the highest recorded temperature of 51.5°C. From September to December the temperature drops dramatically. In January, the coldest month, daytime temperatures range from 10°C to 30°C, falling to below 5°C at night, and on rare occasions dropping below freezing. The mean temperature does not exceed 20°C during November to March. The mean temperature during the summer months is around 30°C. The annual mean temperature is 26°C. The temperature of the sea is 20.5°C during January and 31°C in July. Skies are mostly clear over the country, and Kuwait averages nine hours of sunshine a day (Assessment of groundwater resources in Kuwait using Remote sensing technology, 1992). The annual rainfall in Kuwait usually varies from 75 to 200 mm; with mean annual rainfall of 145 mm. winters can be rainy, but most rain falls in the spring, from February to May. The volume from rainfall is 2600 million m^3 which 160 million m^3 recharge the aquifer and most of it evaporates under extremely high temperature. The mean annual potential evaporation is 4000 mm. The mean humidity during wet season usually exceeds 70 %, and does not drop below 35 % during the rest of the year. In August and September humidity often reaches 100%. The atmospheric pressure oscillates around 1020 mb during winter and 1000 mb during summer. Kuwait has four main seasons and several sub-seasons. They are times of distinct weather, such as dust storms, thunderstorms, or persistent winds. Winter is the wettest and coldest season in Kuwait, characterized by northwest winds. Southeasterly winds may bring rain and an occasional dust storm. During spring, southeasterly winds *suhaili bring* hot air, and the *sarrayat* (local thunderstorm) is common (Parsons, 1963). Summer winds are variable, from northeast, northwest, and southeast, with almost cloudless skies. Sandstorms and very hot northwesterly winds in June and July increase the effects of the summer heat. In the autumn, in November, winds switch from the southeast to the northwest and blow in any direction for several days.

Kuwait is one of the countries in the world without surface water. Its water resources can be classified into three significant categories: (1) natural resource groundwater, and two artificial resources (2) desalinated seawater and (3) treated wastewater. In the absence of surface water, groundwater constitutes the most important natural water resource in Kuwait with TDS ≤ 10000 mg/L in the central and southern areas of Kuwait. Only in the north can one find fresh water lenses in two groundwater fields called Rawdatain and Umm AlAish fields. Rawdatain Bottling Company produces annually from 50000 m^3 form the Rawdatain field. Brackish groundwater is used for irrigation, landscaping, construction work, non-potable use in households and mixing with desalinated water, up to 10%, to make it potable. The occurrence of usable groundwater is limited to the Kuwait Group and Dammam Formation aquifers with salinity ranging between 2500 and 10000 mg/L. The percentage of groundwater from the available water budget is 32% with a possibility to increase the use of groundwater. The brackish water of the country is 15000 to 20000 years old and developed during the wetter periods at that time. The general hydraulic gradient is from the south-west to the north-east and the transmissivity ranges from 10 m^2/d to 1000 m^2/d for the Kuwait Group, while for the Dammam aquifers it ranges from 50 m^2/d and 2500 m^2/d (Al-otabibi and Mukhopadhyay, 2005).

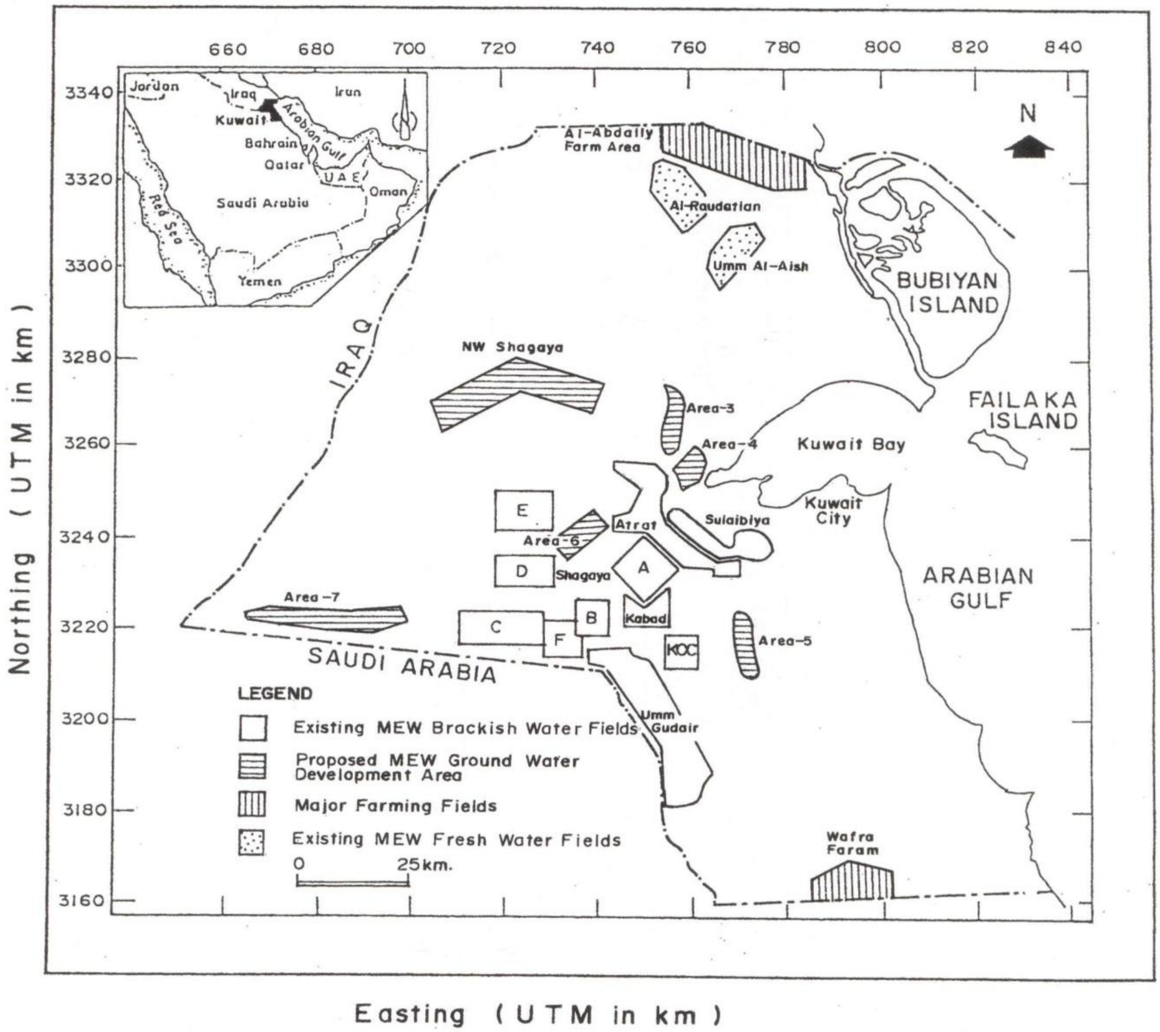


Figure 4 Locations of Water Fields (KISR Report, 1992)

1.3.2 Hydrogeology of Kuwait

In the Arabian Peninsula, there are four systems of aquifers containing sedimentary rocks (Burdon, 1968). The systems are Paleozoic-Triassic, Cretaceous, Eocene and Neogene-Quarternary (Abusada, 1988). Figure 5 shows the generalized stratigraphy and hydrogeological units as described by Mukhopadhyay et al (1996). The Kuwait group consists of a top layer called Dibdibba formation which is only found in northern Kuwait and has fresh water lenses. A shale, clay and cherty limestone aquitard separates the Kuwait Group from the Dammam Formation. Also, the lowest part of Dammam formation combines with Rus Formation to form an aquitard separating the Dammam formation and the UER formation. Groundwater is exploited from two aquifers: the Kuwait Group of the Neogene–Quaternary, and Dammam Formation of the Hasa Group of the Eocene.

The Kuwait Group is unconfined to semi-confined and composed of sandy gravel, silt, calcareous and sandy limestone. The total saturated thickness of the Kuwait Group aquifer ranges from 0 m in the southwest part of Kuwait to more than 240 m in the northeast part of Kuwait. The Dammam formation is a confined layer and consists of dolomitic limestone. The total thickness is varied between 120 m and more than 200 m. The two aquifers connect hydraulically by an upward hydraulic gradient from the Dammam aquifer to the Kuwait group aquifer (Senay et al., 1987). In Figure 6, The initial potentiometric head in both aquifers dropped down since 1960 from over pumping. The water is used for irrigation and for mixing with desalinated water to make it potable.

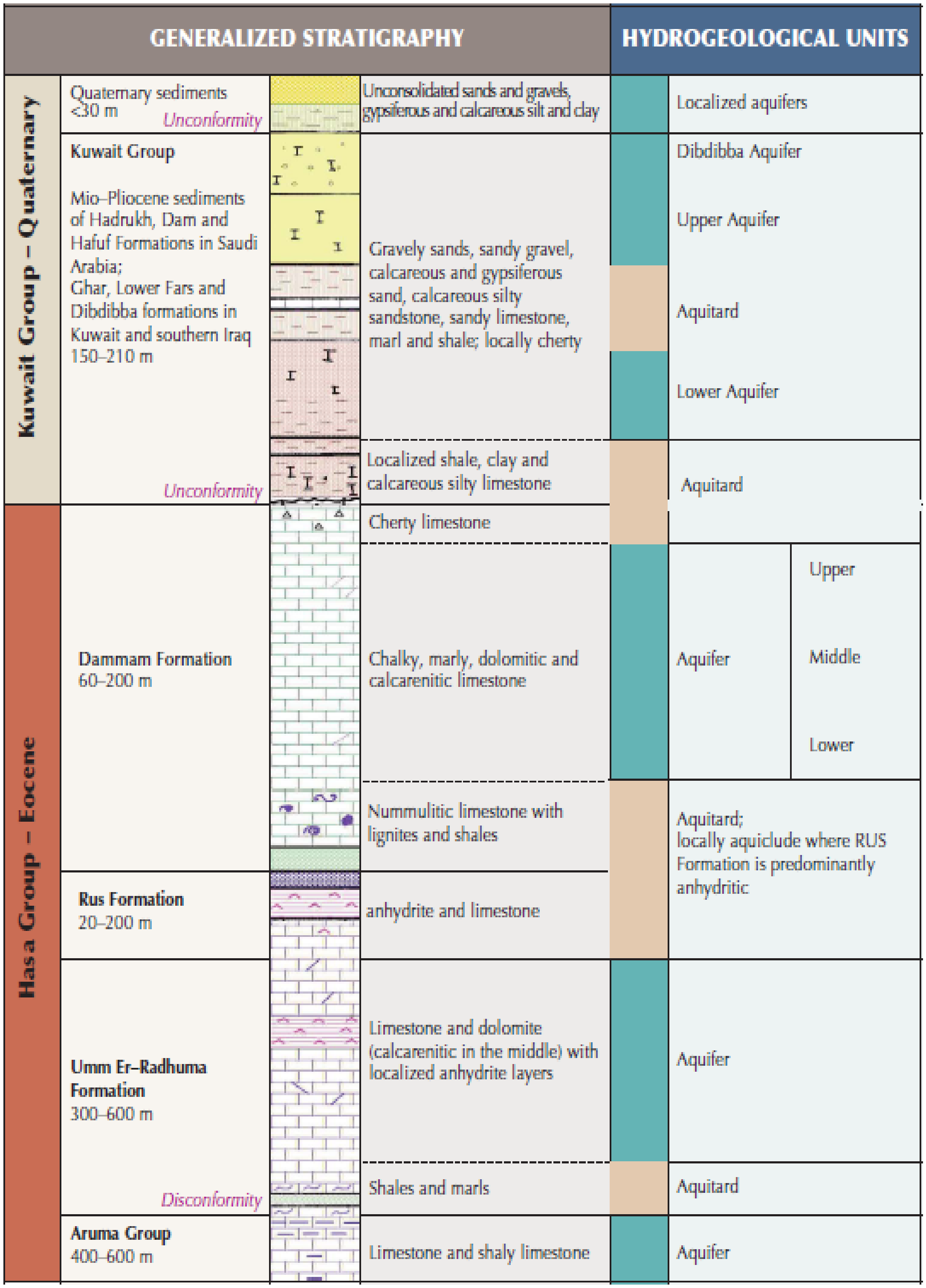


Figure 5 Generalised stratigraphy of Kuwait

A. Mukhopadhyay et al. / Earth-Science Reviews 40 (1996) 259–295

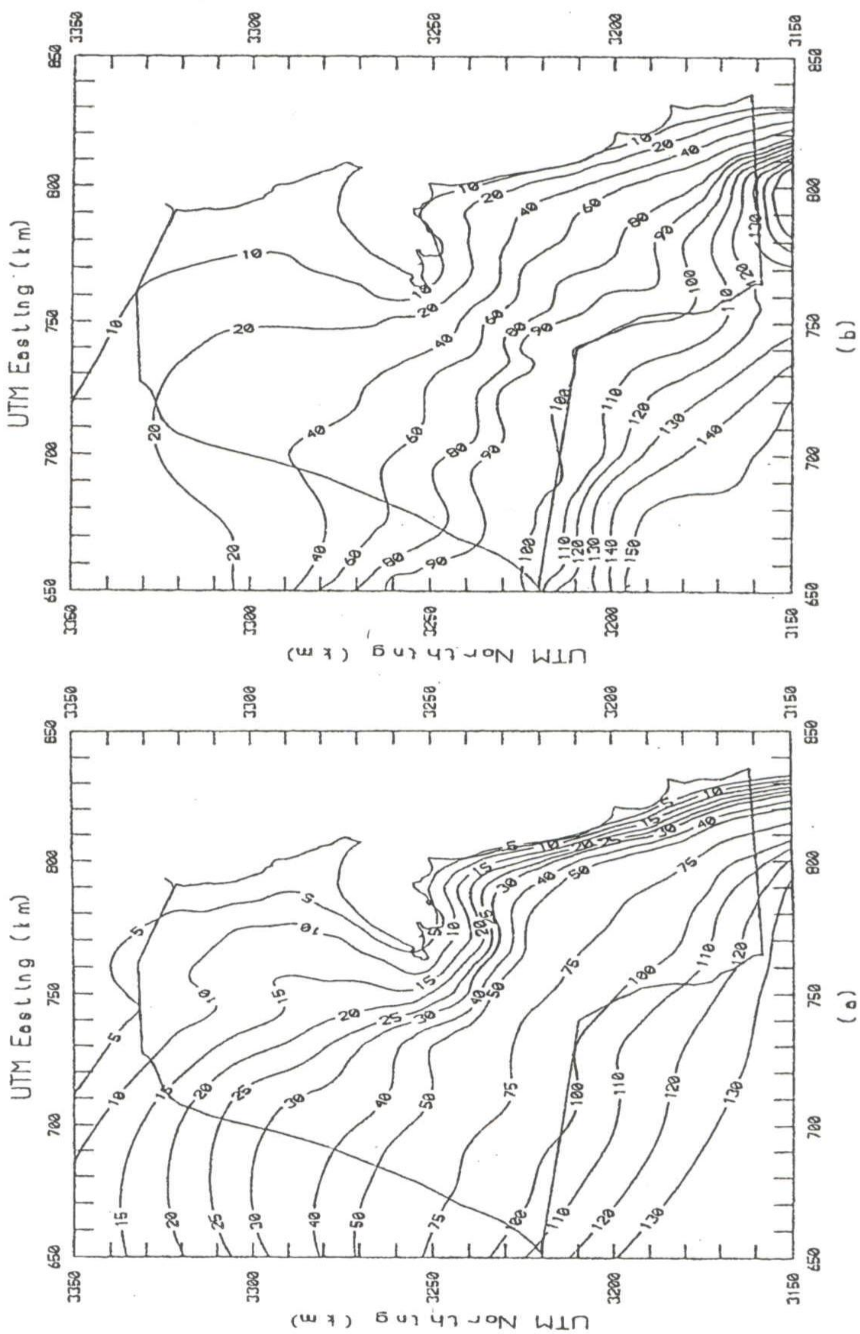


Figure 6 Initial (pre 1960) potentiometric heads in (m amsl) in the (a) Kuwait Group and (b) Dammam Formation aquifers (Mukhopadhyay et al., 1996)

The TDS of groundwater in the Dammam Formation increases from 2500 mg/l in the southwest to more than 10,000 mg/l in the northeast. In the same way, TDS of the Kuwait Group aquifer varies from 4000 mg/l in the southwest of the country to more than 25,000 mg/l in the northeast except in the Dibdibba Formation in the Rawdatain and Umm Al-Aish depressions, there are freshwater lenses with TDS less than 500 mg/L (Source: alrawdatain Bottled Co. www.alrawdatain.com/water.html) formed from the infiltration of runoff generated by infrequent rainstorms (see TDS maps for Kuwait Group and Dammam aquifers in Fig 8). The main standards are those recommended by the World Health Organization (WHO), the European Economic Community (EEC) and the United

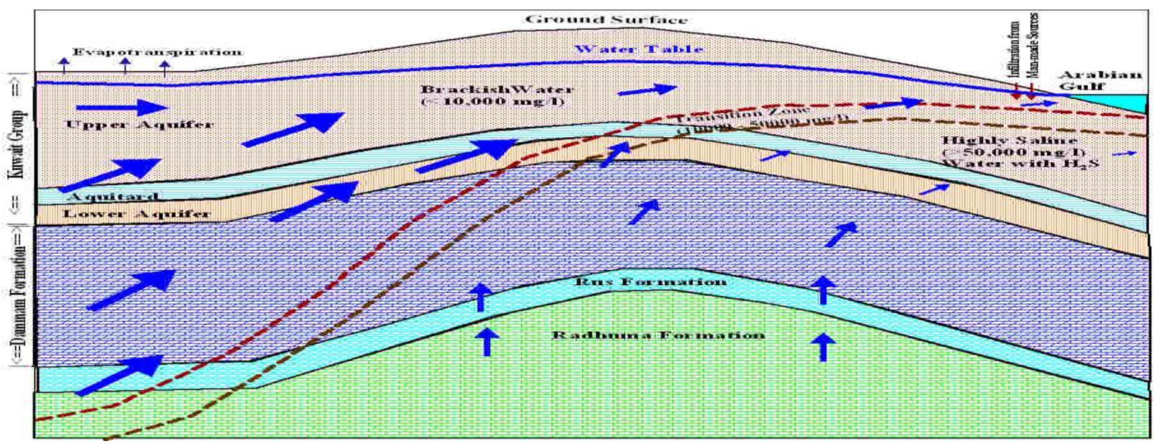


Figure 7 Direction of Groundwater Flow

States Environmental Protection Agency (USEPA). Kuwait’s TDS drinking water standard, less than 1500 ppm, is based on WHO drinking water guidelines The conceptual model for the movement of groundwater in Fig 7 is the best to describe the path of water in the ground from west to east (after Senay *et al.*, 1987). A decrease in the water level in both aquifers of 20m and up to 50m occurred due to over pumping from 1960 to 2000, respectively (Mukhopadhyay et al., 1996).

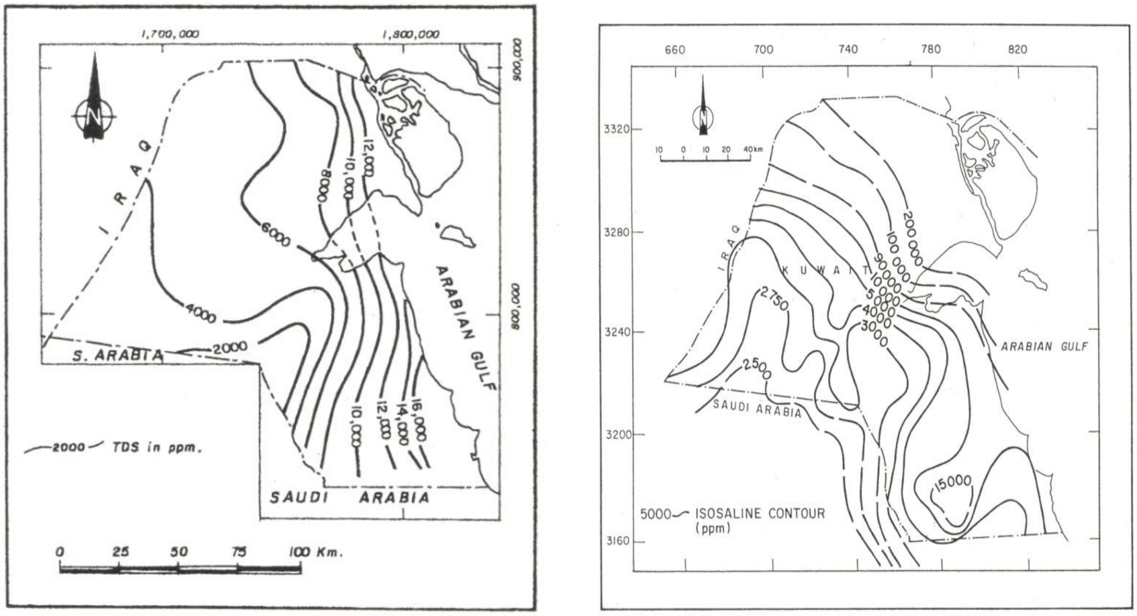


Figure 8 Figure 8 TDS maps for Kuwait group aquifer on the left and Dammam aquifer on the right

(produced in 1994 by MEW)

1.3.3 Water availability and demand

Kuwait has limited water resources represented by small reserves of fresh groundwater and has to rely on several artificial water resources to secure its water requirement, either potable or non-potable water, from desalination plants and wastewater plants. Kuwait has depended almost entirely on desalination plants since 1953 for its drinkable water supply to domestic consumers. The first desalination plant was built with a capacity of 4550 m^3/d in Shuwaikh (MEW, 2006). Kuwait's government had to expand seawater desalination capacity to meet the increasing demand over the years. In addition, there is a great and increasing potential for the use of treated wastewater for such uses as irrigation and developing green lands. Kuwait is one of the world leaders in wastewater treatment. Brackish groundwater has been utilized since 1960 to supply consumers through a separate pipe network for use in landscaping, irrigation, construction work and non-potable use in households. Also, it is mixed with desalinated water, up to 10 %, to make it potable. Kuwait is classified as one of the most water scarce countries in terms of water availability (UN World Water, 2003). The current rates of water consumption are very high, with 459.6 L/C/d and 91 L/C/d for fresh and brackish water, respectively (MEW, 2007). The budget of water resources in Kuwait, represented as percentages of needed water, is 59 % from desalinated plants, 32 % from groundwater with the possibility to increase the use of this resource and 9 % from wastewater treatment plants (Fadlemawla and AlOtaibi, 2004).

1.3.3.1 Production from desalination Plants:

Kuwait was relied mainly on rainfall found near the surface in shallow wells before 1925. But due to the growth of the population that limited source became insufficient to supply the growing demand. Kuwait turned to the Shaat AlArab (Tigris and Euphrates River) for fresh water supply brought by dhows, and a primitive stage and distribution network was established. The situation changed with the influx of oil wealth when the first oil shipment was effected in 1946. Kuwait was the first country to in the world to use Cogeneration Power Desalting Plants (CPDP) in 1953 and adopt flash type technique (MSF) in the Gulf area in 1957. Indeed, before the end of the 1950s, the first desalination plant was operational and produced 4550 m^3/d (Naseeb et al., 2005). Figure 9 shows the production of desalinated water since 1980 till 2005 and Figure 10 shows the percentage of production for each desalination plant in 2005. Sabiya Station is under construction to supply desalinated water for Alhareer City or city of Silk in Sabiya (capacity 227300 m^3/d). It is expected to raise the current capacity MIGPD to 93193 m^3/d at Shuwaikh Station and it is also expected to add new distillation plants (R.O) having capacity of 136380 m^3/d to reach the total installed capacity of 2295731 m^3/d (MEW, 2005).

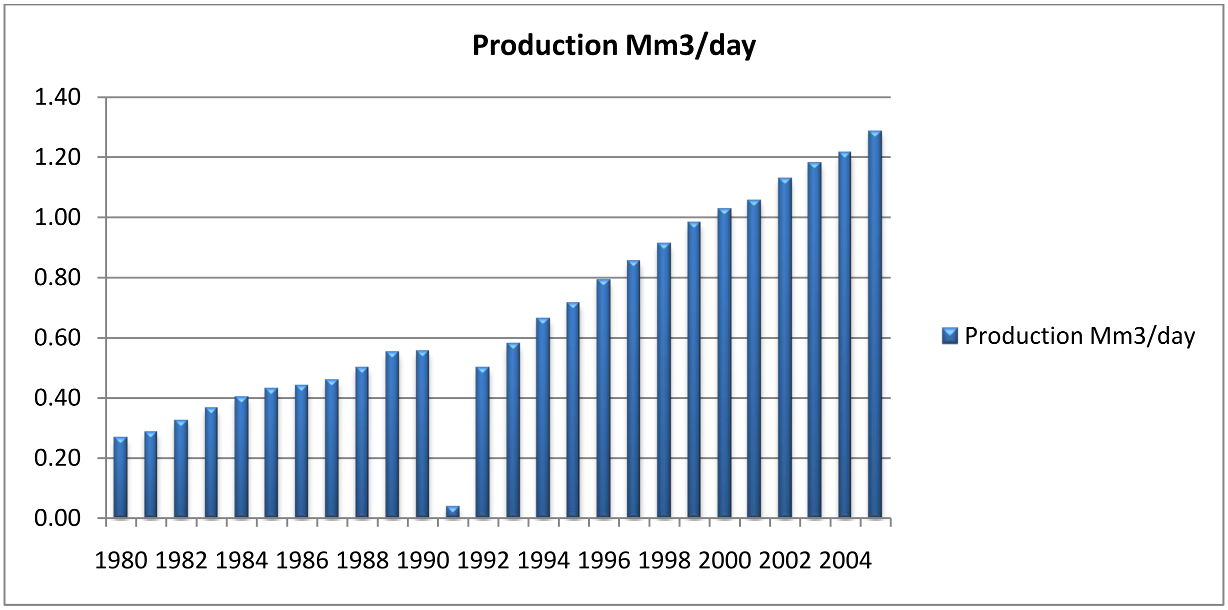


Figure 9 the Production desalinated water from 1980 to 2005 in Kuwait

The production from desalination plants rise steeply year after year to meet the demand of population growth especially when desalinated water makes up more than half of the total water budget in Kuwait. The production reached 1.29 Mm^3/day in 2005, a 25.2 % increase from 2000.

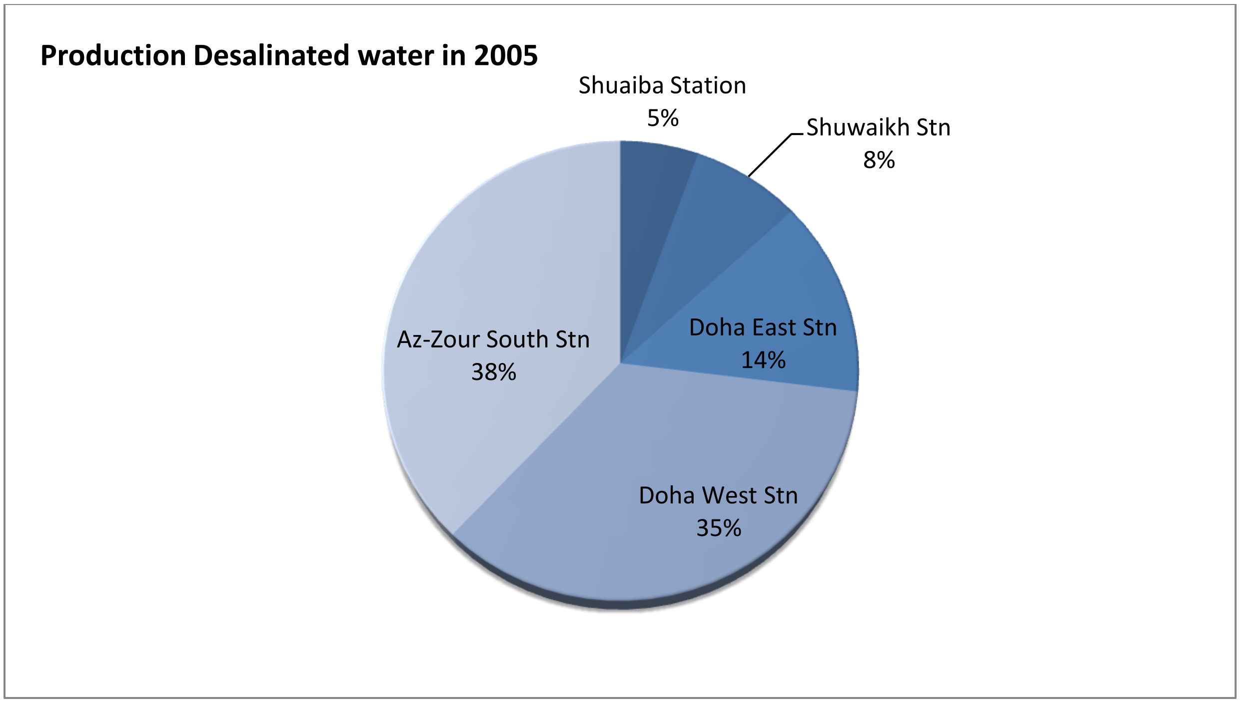


Figure 10 Production from Desalination plants in 2005

Figure 11 shows the production of fresh water from 1980 till 2007, including net desalinated water plus brackish water required for blending. Figure 12 shows the average freshwater daily consumption between 2001 and 2005. The daily average freshwater consumption was high between May and October, exceeding 1.40 Mm^3/day in 2005.

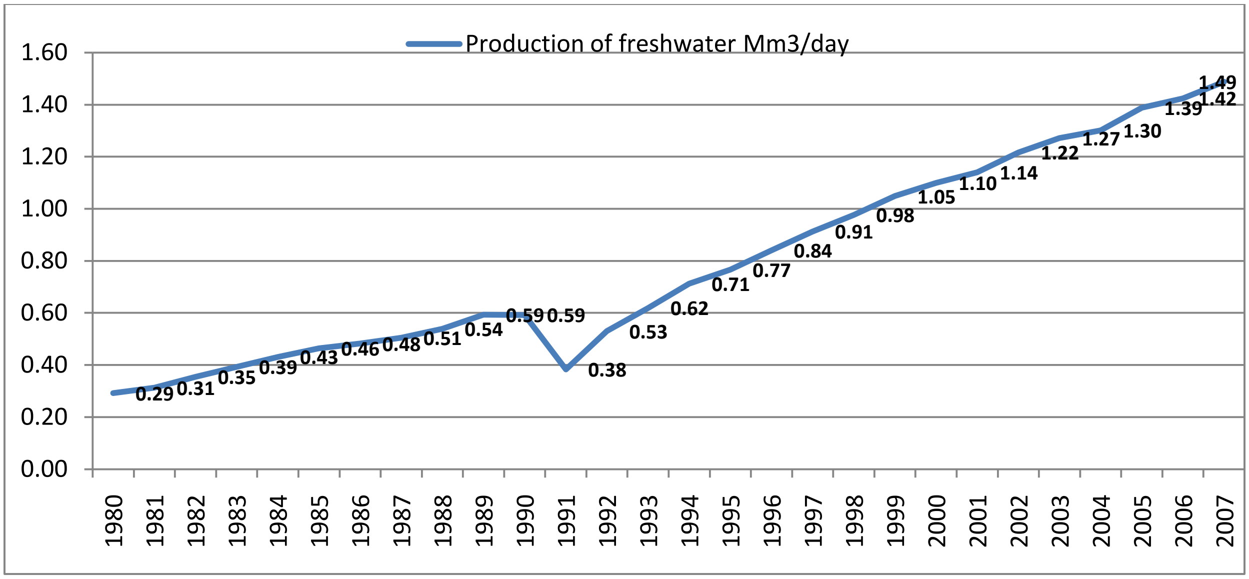


Figure 11 the production of Freshwater from 1980 to 2007

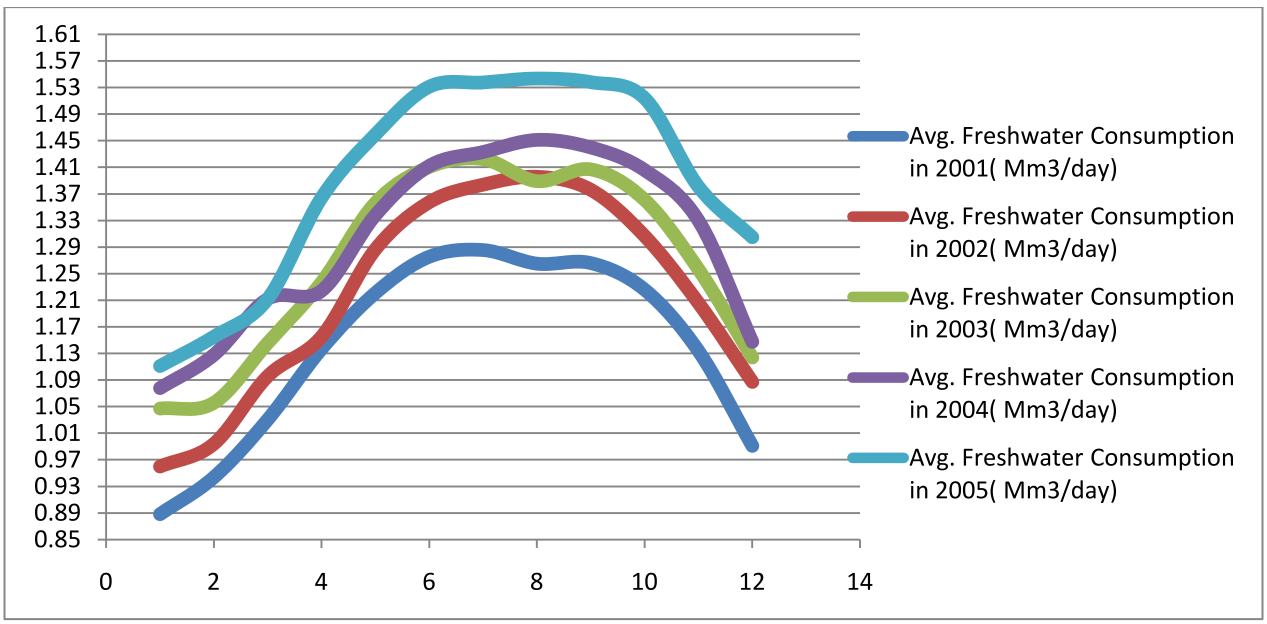


Figure 12 averages Freshwater Consumption from 2001 to 2005

The demand of freshwater increased after 2000 as a consequence of the growing population; the consumption per capita increased and reached the maximum in 2002 of

503.4 L/C/day then dropped down to 459.6 L/C/day in 2007 with a total population of 3,238,035 (MEW, 2007).

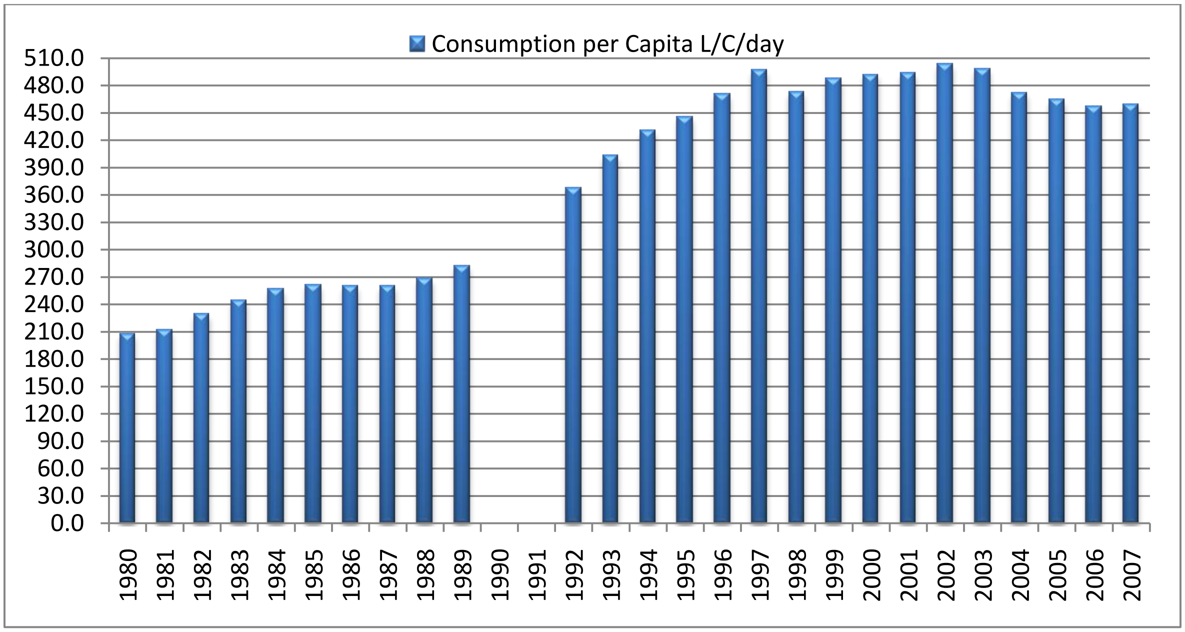


Figure 13 Consumption Per Capita from 1980 to 2007 (L/C/day)

1.3.3.2 Groundwater in Kuwait

Total consumption of groundwater with TDS between 2500 – 5000 mg/L in Kuwait has risen at a very fast rate over the past several decades. The production in 2007 was 146.90 Mm^3/year and the consumption in the same year was 108.38 Mm^3/year. Table 2 illustrates the average daily consumption each month from 2001 to 2005 (MEW, 2006). The current withdrawals of groundwater for farms located in the north (Abdally) and south (Wafra) of Kuwait are estimated to be 0.3 - 0.4 Mm^3/day in each of the areas. The Ministry of Electricity and Water in Kuwait is responsible to supply brackish water to residential consumers through its network.

Table 2 The Annual and Daily Consumption of Groundwater between 2001 and 2005 in kuwait

	2001		2002		2003		2004		2005	
	Consum. Mm3/yr	Daily Avg	Consum. Mm3/yr	Daily Avg	Consum. Mm3/yr	Daily Avg	Consum. Mm3/yr	Daily Avg	Consum. Mm3/yr	Daily Avg
Jan.	5.51	0.18	6.14	0.20	5.77	0.19	6.11	0.20	7.33	0.24
Feb.	5.45	0.19	5.99	0.21	6.13	0.22	6.89	0.25	6.70	0.24
Mar.	7.92	0.26	7.64	0.25	7.95	0.26	8.80	0.28	8.30	0.27
April	9.33	0.31	8.32	0.28	8.69	0.29	9.22	0.31	9.49	0.32
May	10.17	0.33	10.06	0.32	10.30	0.33	10.73	0.35	11.09	0.36
June	10.36	0.35	10.73	0.36	11.18	0.37	11.11	0.37	11.72	0.39
July	10.73	0.35	11.49	0.37	11.50	0.37	12.09	0.39	11.65	0.38
Aug.	11.18	0.36	11.18	0.36	11.79	0.38	12.95	0.42	11.60	0.37
Sep	10.79	0.36	10.69	0.36	11.53	0.38	11.88	0.40	10.90	0.36
Oct.	10.34	0.33	10.10	0.33	11.16	0.36	10.96	0.35	10.91	0.35
Nov.	8.54	0.28	8.19	0.27	8.98	0.30	9.30	0.31	8.96	0.30
Dec.	5.73	0.18	7.23	0.23	6.59	0.21	7.26	0.23	7.36	0.24
Total	106.05	0.28	107.75	0.32	111.54	0.31	117.30	0.32	116.0	0.32

1.3.3.3 Treated wastewater

Water from wastewater treatment plants has become a common practice in many parts of the world. Treated wastewater could be used for aquifer recharge in Kuwait. Mukhopadhyay et al., (2003) concluded that treated wastewater is compatible for use in artificial groundwater recharge and recovery for both main aquifers in Kuwait. It is more logical to use the treated wastewater having a TDS value almost the same as that produced from desalination plants for a country like Kuwait where natural water resources almost do not exist and the cost of desalting seawater is extremely high. In Kuwait there are four wastewater treatment plants with a total capacity of 657000 m^3 /day in 2004, about 30 % of this is used for irrigation and developing green lands while the rest is spilled to the sea. The last wastewater treatment plant, Sulibiya, was commissioned in 2004 using a reverse osmosis system with an initial production of 0.32 Mm^3/day. It is planned to use the treated wastewater for artificial recharge of aquifers and recreational purposes such as artificial lakes and rivers.

Table 3 Production of treated wastewater in Kuwait

Wastewater Plants	**Production m^3/d 2004**	**Projection of Production in 2015**
Ardiya		
Riqqa	337000	635600
Jahra		
Sulibia RO	320000	643000
TOTAL	657000	1278600

1.3.4 Surface and Subsurface storage

In Kuwait the surface storage is used for emergency conditions such as when desalination plants shut down or the demand exceeds supply. The available freshwater storage capacity was 11.7 Mm^3/day in 2006 and that represents ground storage and towers storage (MEW, 2007). The demand in that year was 1.42 Mm^3/day which the stored water could supply in normal conditions for almost one week and this is not enough time to maintain and bring the desalination plants on line. Increasing the capacity of surface storage facilities to supply water in emergency conditions for longer times is very expensive. A study provided from Ministry of Electricity and Water compared the total cost of surface storage, desalination plants and aquifer storage and recovery to supply 45469^3/day. The total cost for surface storage is \$ 1442 Million while to construction a new desalination plant is \$ 103.5 Million plus the operation cost of \$ 7 Million. Using the aquifer as subsurface storage cost \$ 25 Million which is less in cost and does not need a vast area. The ASR system is considered to be a sustainable groundwater tool that can help and improve the subsurface water. The aquifer can store huge quantities of water, more than surface storage, without losses from evaporation. The storage is a complementary source when demand exceeds supply in dry times. Nevertheless, evaporation from surface storage results in large losses of water during the year, which may contribute to water shortages in times of water scarcity. Surface storages (reservoirs and tanks) are more vulnerable to risk of contamination (direct contact to industrial pollution sources) and sabotage. In other hand, the ASR system is safer and offers more protection from tampering. ASR systems are considered to be more environmentally friendly than surface storages. Enormous investment is required to construct surface storage and they need for vast area to build in the surface storage. In contrast, subsurface storage requires less cost and land requirements are minimal (an acre or two per well). Fig 14 shows the increase in the capacity of surface storage with the number of storages and Table 3 illustrates the production from water fields.

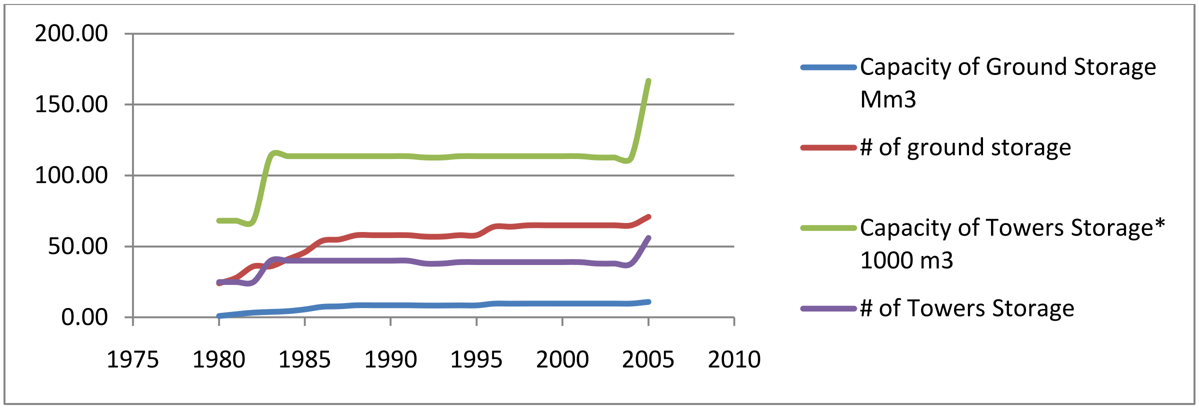


Figure 14 Capacity of ground storage and towrs storage

Table 4 Daily Production from Groundwater Fields

Groundwater Fields	**# of wells**	**productivity capacity m3/D**	**TDS**
Rawdatain Field	14	9092	1000 - 600
Shagaya Fields A	13	31822	3250
Shagaya Fields B	16	36368	3000
Shagaya Fields C	32	81828	2800
Shagaya Fields D	24	54552	2800
Shagaya Fields E	30	68190	4200
Sulaibya Field	105	68190	4000
Um-Qudair Field	67	181840	3700-4100
Wafra Field	2	22730	4500-5500
Al-Atraaf Field	84	136380	4000-4500
Under Construcction Fields			
Field North West of Um-Qudair	19	45460	3500-4000
Kabd Field,North East of Um-Qudair	32	68190	4000-4500
Field North West of Shagaya	85	113650	4500-5500
Future Fields			
Al- Wafra Field	3	31822	5000-6000

The deficit in supplying the freshwater in summer months is one of the problems of supply and demand in Kuwait. The surface storages are used to meet the demand during the critical time. The limited capacity and high contraction cost for surface storage are forcing the decision makers to find a management water resource tool to supply water in the time of needed and reduction the pressure on the desalination plants. Also, it needs a management water resource tool to be environmental friendly and small capital cost with high productivity. ASR technique is the best management water resource tool to meet the following requirements.

- The ability to assign the recovery volume in time of needed.
- The land use is extremely small for ASR field, Comparing to surface storage.
- The productions from wastewater treatment plants are very high in Kuwait and just used in restrict scale.
- ASR technique can remove the stigma of treated water as derived from wastewater by injecting them in ground and recovered as groundwater.
- Regarding to the capital cost of other water supply alternatives, ASR is less than half capital cost of them.
- Improve the water quality of groundwater in Kuwait.
- Groundwater levels can be restored with using the injection and recovery cycles.

The supply and demand of water resources in Kuwait has defined in this chapter with the possibility problems that might face the ground storage (alternative water resource option) in supplying for a long time to meet the demand during the critical time. Also, the best management water resource tool to solve these problems is ASR technique. Next Chapter is the previous experience of using ASR tool in supply the freshwater and improves the water quality of groundwater in local and global scale.

CHAPTER 2: Literature Review

Artificial recharge is practiced throughout the world to sustain and improve groundwater and serve as a second source of water to meet the demands of population growth. It is considered nowadays as a basic concept which can be applied by different techniques (ASR, ASTR, Bank filtration, Dune filtration, Infiltration ponds, Percolation tanks, Rainwater harvesting, SAT, Sand dams, Underground dams and Recharge releases) and in different environmental regions (high or low evaporation and arid or semi arid regions). Many authors and researchers have been addressing constrains for developing artificial recharge in general and in particular the Aquifer Storage and Recovery (ASR) method.

2.1. ASR

Aquifer Storage and Recovery (ASR) has been publicized by different authors and engineering organizations but the most progress in this technique has come from David Pyne. He published his first book as a guide to Aquifer Storage Recovery in 1995 and this has been a basic reference for many researchers and engineers, helping them to develop the management of water resources and groundwater in particular. Pyne (1995) emphasized the role of ASR as a management tool throughout the world and developed the way to use the dual aquifer functions of recharge and recovery. His vision is to utilize an aquifer that contains brackish or poor quality water and not only to inject water into the ground, but also, at the same well, to recover the water to meet the demand in an environmental friendly manner. Pyne (2005) defined many sub-topics that are important when initiating an ASR operation, such as target storage volume (TSV) that is the total volume of water needed for recovery phase and the total volume needed in transition zone separating the storage zone from the native groundwater in aquifer. Also, he concluded that factors that control the selection of a suitable site for ASR: thickness of aquifers, hydraulic characteristics and water quality. He explained how to measure the volume of water to inject into the aquifer depending on the water source, water demand and water quality. In addition, he estimated the starting point to find the TSV as the volume of the storage zone and it should equal to volume of buffer zone in the first injection period to create an appropriate buffer zone. He suggested studying the hydrogeology and evaluating the hydraulic parameters of the site carefully because these are the most important criteria for selection of suitable subsurface storage. The assessment of successful ASR operations depends on how much water can be recovered relative to the amount injected. This is the Recovery Efficiency defined as the volume that meets the minimum Total Dissolved Solid standard divided by the volume of water injected into the aquifer. He presented many scenarios illustrating how to increase the Recovery Efficiency by increasing injection-recovery cycles when the same volume of water is stored in each cycle. The benefit of cycles is created the creation of the buffer or transition zone, which takes time to separate the native groundwater and the storage zone. His vision of using the injection-recovery cycle is not only to create the buffer zone; it is also to leave a small volume of injected water in the ground to restore depleted groundwater reserves. He listed 22 types of ASR applications that can be used for the management and planning of groundwater. He studied many projects currently in operation in the United States to explain the process in different areas. Most of the projects had been using ASR since 1983 and the recovery capacity of these projects is between 2000 m^3 per day to 385000 m^3 per day. The efficiency of recovery of these systems had been improved using the injection-recovery cycles. The author explained the challenges that faced the ASR project such as physical, chemical and biological factors that cause well plugging. He presented the benefits of using brackish water aquifers as storage for treated wastewater and surface water that has high TDS in many states, for example Florida, Texas and Nevada. In his opinion, ASR is an economical water supply alternative which usually meets water demands at less than half the capital cost of other water supply alternatives such as treatment plants or wastewater treatment plants. He estimated that the cost of construction of water treatment plants and surface storage to meet increasing demands exceeds the cost of ASR by 85%.

Many authors reported and described the features and benefits of applying ASR and addressed some recommendation to develop the technique. Dvoracek (1986) explained the opportunity of using artificial recharge as an aquifer management tool. He concluded that any ASR system encounters several points, the availability of water of good quality, the possibility of pollution reaching the groundwater, the ability to operate and maintain the dual well system so as to provide water at an acceptable cost. He mentioned that the next step in developing this technique is improving the efficiency and productivity of the recharge.

Lichtler et al. (1980) carried out research to focus on the technical feasibility of artificially recharging aquifers in Nebraska through wells and surface spreading. He determined the causes that reduce the capacity of production in the recharge phase. These were as follows: entrained air in injected water, suspended sediment in the well, bacteria growth between the injected water and the native groundwater by chemical reaction.

Volker (1986) carried out an investigation to determine the efficiency of artificial recharge of unconfined layers with water supply from the Burdekin River in Australia. He found the critical factors affecting efficiency of the system to be the quantity of suspended sediment, bacteria growth and the hydrogeological properties such as porosity and hydraulic conductivity. He encouraged doing more survey and data collection before initiating any injection operation to avoid clogging, this information can help other researchers in the future to develop management options to increase the efficiency of injection water operation.

Brown et al. (1985) identified the factors leading to the success of injection of water from playa lakes through wells into the Ogallala aquifer in Texas. The factors were the hydrogeology of the aquifer, the total suspended solids of the injected water and the type of injection used. They noted the zone with secondary porosity that resulted from native water solution of calcium carbonate increased the available storage during the injection phase. Air entrapment was prevented from pressure recharge to help in expedite the injection.

In another site in Texas, Sheng (2005) discussed the benefits from using reclaimed wastewater as a source for an ASR system in the Hueco Boson aquifer in El Paso. He classified the ASR system as a general operation with four important points: water source, the aquifer capacity, injection and recovery facilities. The ASR system in El Paso had to restore depleted groundwater in the last 18 years by injection of reclaimed wastewater into the aquifer.

Zikmund et al. (1996) investigated the artificial recharge Colorado River water in an alluvial fill artesian aquifer in Nevada. The total volume injected in the aquifer for later use was more than 123000 km^3 annually until 1996. He concluded the artificial recharge helped to decrease the drawdown in the aquifer and restore the water levels over 10 meter more than the 1990 level.

2.2. ASR in Kuwait

ASR has been investigated and studied by the Kuwait Institute for Scientific Research (KISR) and the Ministry of Electricity and Water in Kuwait since late 1988, but artificial recharge in general was first tried by Parson in 1964 (Senay, 1977). Amit Mukhopadhyay is a researcher in KISR, which is considered the leader of this field and in general of groundwater in Kuwait. He helped develop the ASR technique and his assumptions are considered the basis for many studies by other authors and researchers. Mukhopadhyay et al. (1998) drew attention to the necessity of having large storage of water in aquifers to meet demands during emergency conditions such as desalination plant breakdown or damage to surface storage. The results of previous reports and projects have been reviewed in this study. He reported injection rates of 650 to 1300 m^3 per day through multiple wells and he estimated the rate of recovery of 45000 m^3 per day based on the average per capita demand of fresh water in Kuwait. This should decrease in an emergency condition to 30 L per capita per day and represents the consumption of drinking and cooking (Agnew et al., 1992). He presented data from a trial injection and recovery test that showed that the recovery efficiency, which is the most critical factor of success, was less than 20 % in the Dammam formation aquifer. He explored the criteria for site selection for artificial recharge based on his study in 1994. These were as follows: the TDS should not be more than 5000 mg/L because he wanted to decrease the TDS difference between the native groundwater and the injected water. The transmissivity of the aquifer (between 150 and 400 m^2 per day) controls the movement of water through the aquifer. He recommended injection in the Dammam Formation aquifer instead of the Kuwait aquifers based on injection-recovery tests that concluded that the clogging problem is less in the Dammam aquifer. The hydraulic gradient should be as nominal as possible. He concluded that subsurface storage is a feasible and economic option for Kuwait, and it depends mostly on desalination plants to meet the demands.

Mukhopadhyay et al (1997) carried out a laboratory investigation of the compatibility of the Dammam aquifer with desalinated water. He concluded that after drilling a well in the Dammam aquifer that the injection of desalinated water into the aquifer within the selected site should not have any compatibility problems. The clogging rate affect on the rate of injection, is increased during the long-term injection phase and decreased in the daily injection phase.

Mukhopadhyay et al (1994) explored the potential of artificial recharge in Carbonate and Clastic aquifers of Kuwait. They evaluated the technical feasibility of injection and recovery operation. They presented three experiments in different sites to monitor clogging from suspended solids and air entrapment. They presented aquifer and well parameters used in the evaluation which helpful for many study in this field. He concluded that the injection in the Kuwait aquifer (Clastic aquifer) was extremely difficult due to the high rate of clogging.

Al-Otaibi et al. (2005) emphasized the role of managing water resources in Kuwait. He referred to the increasing population and standard of living that will increase the demand for fresh and brackish water and cause extreme stress in the desalination plants and aquifers. He presented data for the current consumption and water availability that is mainly met from desalination plants and brackish groundwater. There is another source that can meet the demand and be integrated with the management of water resources, which is the treated wastewater coming from four wastewater treatments plants. He suggested using treated wastewater for artificial recharge instead of desalinated water to restore the groundwater level and make the brackish water a supply for gardening and outdoor use daily instead of on specific days. He described the benefits of aquifer storage as being more economic than surface storage; it does not need a large area for the storage and the need to establish an expert team that can deal with integrated water resources in the country. The treated wastewater has TDS meeting quality standards for drinking water but consumers are not satisfied to drink it but you can get rid of its stigma as come from wastewater when storing in aquifer and recovered later as natural groundwater. The main role of ASR is as subsurface storage; he mentioned that aquifers can be used as storage to meet the demands in a major disaster such as vandalism, wars or environmental issues; as a result the study concluded that a strategic reserve of potable water in aquifers should be created.

Darwish et al (2009) investigated the need for sustainable water management in Kuwait. They presented the total production and consumption of all water resources (desalination, treated wastewater and groundwater) and the history of water development in Kuwait. Multi-stage flash is the method for filtering and desalinating the seawater in Kuwait, but it has a high energy consumption and maintenance cost. They considered the integrated water resource management and improvement of the interaction between water agencies to develop non-conventional resources in the country. The integrated water management plan suggested by the authors is highlighted and shown to be more efficient when it is used to develop the resource. Managing groundwater, desalination plants and wastewater treatment plants are described with priority to increasing sustainability and decreasing the cost of energy consumed. The pricing and consumption of both fresh and brackish water should be reconsidered due to the high per capita demands that came from bad practices such as using hose-pipes for washing cars and pavements. They suggested using the treated wastewater from the new wastewater treatment plant. This plant uses a Reverse Osmosis treatment system and is one of the largest treatment plants in the world. The effluent could be used for artificial recharge to create aquifer storage to sustain the other resources and meet the demand in certain conditions and restore the water level of groundwater. The aquifer can be used as a natural filter to remove most of the suspended solids, bacteria and viruses. They concluded that the treated wastewater used for artificial recharge should rise to full capacity and reduce the stress on the other sources especially the vulnerable desalination plants.

Mukhopadhyay et al (1994) described the application of VTDN software of the Bureau de Recherches Geologiques et Minieres (BRGM) of France as a management tool to evaluate the options and plans for improving the groundwater of Kuwait from 1995 until 2010. They described the most important parameters as input to any groundwater software such as hydrogeology, hydrometeorology, hydraulic parameters and water quality. The results from different scenarios show that the water level in both aquifers in that year (Kuwait group aquifer and Dammam formation aquifer) will continue to decline until the end of the simulation. They encouraged using artificial recharge to restore water levels and maintain water quality in the aquifer systems under consideration. The results showed the effect of injected water on the aquifer parameters such as hydraulic conductivity and potentiometric head in the aquifers.

The objectives from the literature review and the previous ASR studies in both the global and local scale were to identify the technique in general and the progress that has been made for the management of water resources and illustrate some of the important lessons learned from the prior study to use later in the methodology chapter.

The next step will be the technical chapter, which repots the creation of a GIS Groundwater database for Kuwait to be used in the modeling part and as reference for the prospective study. The GIS will illustrate the suitable sites for ASR operation based on the input of selection criteria. Design of the ASR operation is the following step, which includes the criteria to find the volume of injection and recovery and the duration and number of cycles for the operation achieve the desirable percentage of recovery efficiency. The last step defines the software that will used to show the scenarios of injection and recovery. The results from the software will determine the target storage volume and the movement of injected water and native water within the target zone.

CHAPTER 3: Methodology

This chapter describes the way and mechanism to initiate a dataset for groundwater of Kuwait in ArcGIS and apply the Aquifer Storage and Recovery (ASR) method in Kuwait to get subsurface storage that sustains other water resources to meet the demand. Kuwait desalination plants have supplied drinking water since 1953 to consumers and households usage. With the steep rise in population in Kuwait, the demand on freshwater has been high which drove the government of Kuwait to meet the demand by extending and building desalination plants with high capacity and technology. The production from groundwater participates in the water budget by supplying irrigation, non-potable use in households and mixing with desalinated water. In view of this strategic water option, Kuwait has built surface reservoirs and towers to sustain the desalination plants when the demand exceeds the supply. The total surface water storage capacity of reservoirs and towers is about 11.73 Mm^3 while the daily demand per capita in 2006 was 459.6 liters per capita per day (L/C/D) (MWE, 2007). If all of the desalination plants were out of commission or service for technical reasons, such as breakdown, then water supply will depend mostly on surface storage. On the other hand, the surface storages have the ability to supply fresh water for up to seven days and 21 hours. The available supply from surface storage is not sufficient to meet the demand, especially given the more than one year it takes to bring the plants back online. In addition, the surface storage is easy to sabotage, which keeps the country without water security in such an emergency condition.

Kuwait needs a source that has dual purpose to meet the demand when non-conventional water resources production are less than the demand or out of service and improve the natural water resource. ASR technique meets this standard of requirement and has been practiced in different countries. The general definition of ASR is simply putting water in the ground and bringing it back in time of need. The success of ASR as a water management tool in Kuwait can be measured by many factors. To use the ASR as secondary source to achieve sustainable management requires extensive hydrogeology data for sites in Kuwait. Geographic Information Systems (GIS) are a powerful way to transfer most of the hydrogeology data, such as maps, tables and numbers, to displays in software such as ArcGIS that can interpolate the date to cover the country. The benefit from transferring all of the data to GIS is to create a database for water resources of Kuwait which is easy to update after a time of period.

Selecting suitable sites for applying ASR is an important factor that should consider many hydraulic and economic parameters. The volume of water that needs to be injected and recovered is the most essential to building a conceptual design for ASR operation that also considers the daily volume of demand and supply. After identifying alternative sites and volume needed to be recovered, numerical modeling can play the role of simulating many ASR operating scenarios that will optimize the recovery volume under controlled hydraulic conditions. The methodology is a series of main steps starting with collecting all of the data from different sources to build the GIS database for water resources of Kuwait that can be used to assist in to choosing suitable sites for ASR. Based on the required recovery volume, hydraulic parameters are imported from the GIS database, and then many scenarios can be simulated in a groundwater model to give the volume and time of supply of the water from ASR.

3.1. Database in ArcGIS:

Collecting the data related to the water resources of Kuwait from different sources and putting them together in ArcGIS, is the first step to initiate a database for most of the information to help decision makers and researchers do their work in more efficient way. The data required for ASR includes such things as transmissivity, water quality, and water level for each aquifer. Also, the top elevation, thickness and hydraulic parameters are important to understanding the path of flow in the subsurface. In Kuwait, usable groundwater exists in two productive aquifers, the Ecocene Dammam Limestone Formation and the Mio-Pleistocene Kuwait Clastic Group. The groundwater fields have been restricted by the Ministry of Electricity and Water Resources based on many criteria, for example the water quality and populated areas.

Desalination and wastewater treatment plants have been in production since 1980 and the type of system used in each plant will have an attribute table in ArcGIS. Excel files for desalination plants and wastewater treatment plants containing all the information about the process and production have been imported and linked in ArcGIS. The same has been done for each groundwater field including information about the daily production capacity and approximate number of wells in the field. The table 5 below shows in details all of the information that has been imported to displaying into ArcGIS using GCS_WGS_1984 as the Geographic Coordinate System and

WGS_1984_UTM_Zone_38N as the Projected Coordinate System. The hydraulic and hydrogeologic parameters have been investigated and represented for many years as contour maps. The lines of the contours are accurate but if the area of interest lies between two contours lines then it the value of the parameter must be estimated. The most recent maps for properties of groundwater in Kuwait and its hydrogeologic parameters come from Kuwait Institute for Scientific Research (KISR) in clear contour maps. In contrast, most of older maps were not clear in describing the values. In the figure below a TDS map of the Dammam aquifer is shown (Citation: KISR, 2009).

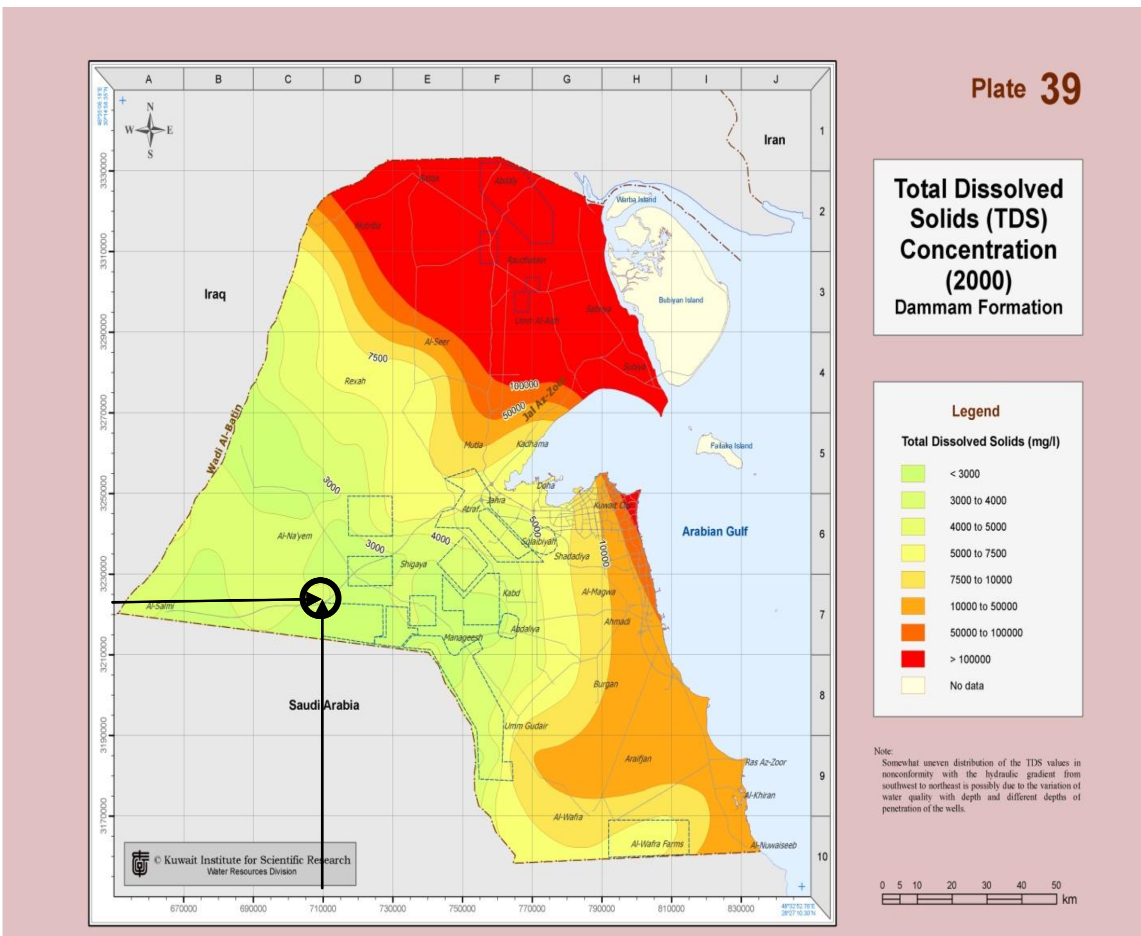


Figure 15 TDS of Dammam Aquifer (KISR, 2009)

Table 5 Description for the Feature Classes in ArcGIS

Feature class	Description to the feature class	Shape of the feature
Desalination plants	- Each desalination plant is represented on the Kuwait map with X and Y coordinates - The total production and capacity in m^3 per day - Total number of units in each plant	Point
Wastewater plants	- Each treatment plant is represented with X and Y coordinates and has the approximate total production for each of them	point
Groundwater fields	- Groundwater fields occupy a restricted area with a total number of wells and the capacity of the field in m^3 per day	Polygon
Demands, Supply and surface storage	- It is represented by the total consumption and production of freshwater every year - The available surface storage in m^3 and number of surface storage objects. - Total consumption per Capita in L/C/D	polygon

It has been following each point is located on the contours line and record them in X and Y coordinates for transmissivity map, water level map, water quality, top elevation and thickness for Kuwait aquifer, Dammam aquifer and the aquitard between them (an average value for the aquitard between the two aquifers was estimated). Display the points in ArcGIS, for instance the TDS of the Dammam aquifer and connect each point that has the same value together to represent a polyline with a unique value using the Editors tool. Some of points are connected using the curve command to be identical to the original map. At the end all of the points are connected, each hydraulic parameter and hydrogeologic data has a feature class including polylines representing the value of the contours. The purpose of transferring all of the contour values is to find the value between contours in ArcGIS. A TIN surface is created from vector data, such as polylines containing values, using the ArcGIS 3D Analyst TIN Creation tools. A TIN can be built by triangulating a set of vertices. The vertices are connected with a series of edges to appear as a network of triangles.

Figure (16) shows the process of creating the TIN feature. It is created for all of features that have polylines using the same process. The next step in 3D Analyst is to convert the TIN feature to a Raster - cells that represent or define a class or group of values.

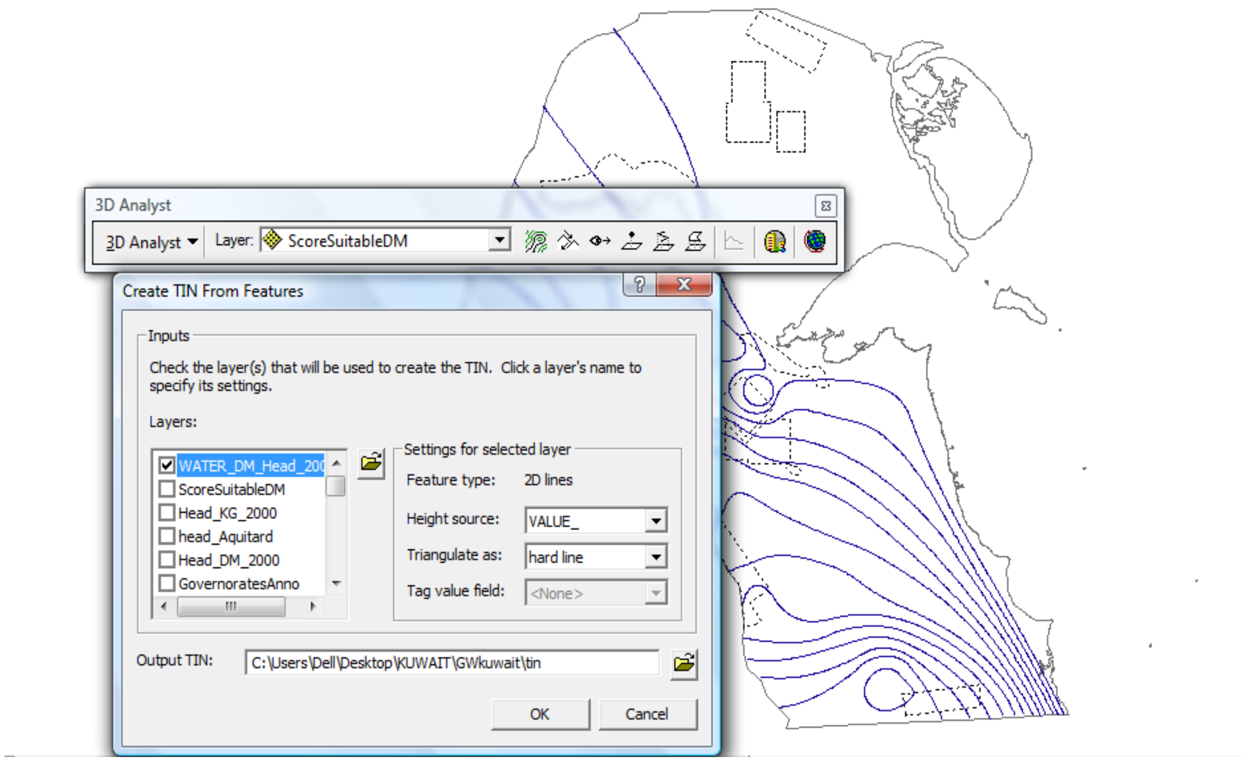


Figure 16 the process of creation TIN

In the raster, it can find the precise value for any hydraulic parameter at a specific site; this is better than using the older maps that might not give exact values because there is a high probability of human error. The approach used here is to have all of the required data in rasters and to use them in visual analysis operations such as a mathematical function to measure the distance and surface analysis (slope) (Maidment, 2002). The spatial analysis tools in ArcGIS can perform a range of powerful spatial modeling and analysis on raster and vector data sets. It can apply mathematical functions which are useful to derive the hydraulic conductivity of an aquifer. Using the Raster Calculator in Spatial Analyst, dividing the transmissivity raster by the thickness raster of an aquifer gives the hydraulic conductivity within the Kuwait map. Also, spatial analysis can help to find suitable areas by adding the selection criteria in the Raster Calculator as described below.

The objective of this stage was to create a database with most of the information for water resources of Kuwait in GIS data format which will help to find the suitable areas for ASR operation and numerical modeling to simulate the flow and movement of water in injection and recovery phases in certain conditions.

3.2. Selecting suitable sites for ASR in Kuwait:

There are many considerations for selecting sites for ASR injecting and recovery operations. These can be classified into non-technical (social and general) and technical criteria. The non-technical factors include the location of the water source that will supply the ASR operation, proximity to populated areas and the total surface area required for ASR facilities. These factors will be determined after identifying the technical criteria that are related to the storage zone characteristics in the aquifer.

The study will be focus on the Dammam aquifer that is a confined layer which is preferred for ASR operations and many studies have been carried out to measure the feasibility and compatibility with injecting freshwater into the Dammam aquifer. This study will build on the basis of on these studies prior studies (Mukhopadhyay et al., 1994).

Transmissivity in the Dammam aquifer ranges from 50 m^2/ d to 2500 m^2/ d (Al-otaibi and Mukhopadhyay, 2005). It represents the product of hydraulic conductivity and aquifer thickness. To get high recovery efficiency, transmissivity in the target aquifer must be neither too high nor too small; it should be moderate. The high transmissivity causes a high probability of mixing with native groundwater; as a consequence, the recovery efficiency will be less than the desirable limit. On the other hand, low transmissivity will increase the recovery efficiency while it restricts the injection rate per day (Mukhopadhyay et al., 1992). The best scenario is to have moderate transmissivity in the target aquifer; thus, lowering the injection over the cycles (Pyne, 2005). The moderate transmissivity of the Dammam aquifer should be between 150 – 1000 m^2/d while the most suitable aquifers are restricted to be between 200 – 400 m^2/d to get the most accurate sites.

The depth of the water table plays an important role in selecting the suitable site; a deep water table will increase the cost of pumping and deep excavation of the ASR wells. In case the water table is near the ground level, there is a probability of rapid rise in the water table that might exceed the ground level elevation. The normal range for the injection phase is between 50 and 150 m below ground level (Pyne, 2005). Since one of the benefits of applying ASR in Kuwait is to restore the water level in the aquifer, the range of depth of water below the ground in in the most suitable sites should be less than 90 m and more than 50 m. An Excel file of depth of water below the ground was imported into ArcGIS and displayed in X and Y coordinates. Spatial Analyst was used to interpolate the value of points using the kriging method to a raster layer covering most of the country.

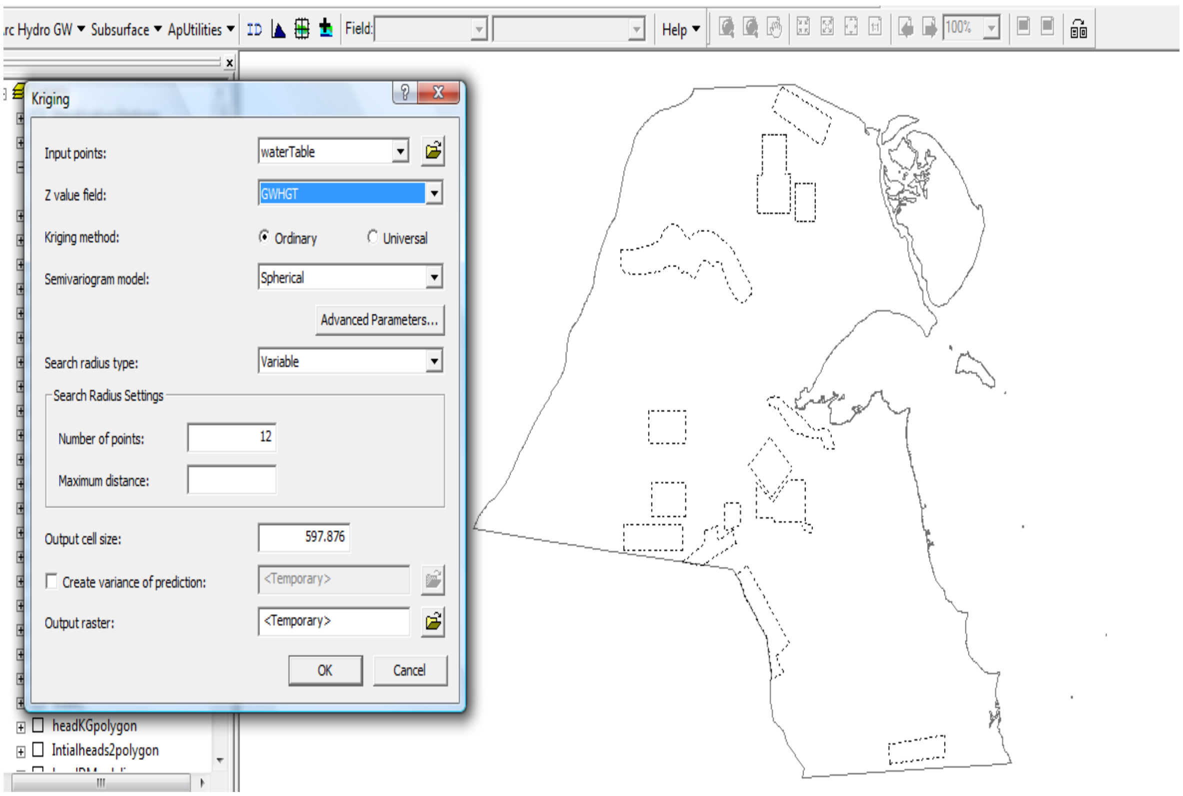


Figure 17 The Process to interpolating the value of piezomentric head level in ArcGIS

The hydraulic gradient is the difference in piezomentric head level between two points over the distance between them. Most of projects that used ASR recommended that a site should have as horizontal a hydraulic gradient as possible. The slope in selecting the preferred sites should be less than 0.25. There was no raster layer created for hydraulic gradient in the first stage but the Surface Analyst in ArcGIS can derive the percentage slope from the head level in the Dammam aquifer created from converting the head level raster to a point feature.

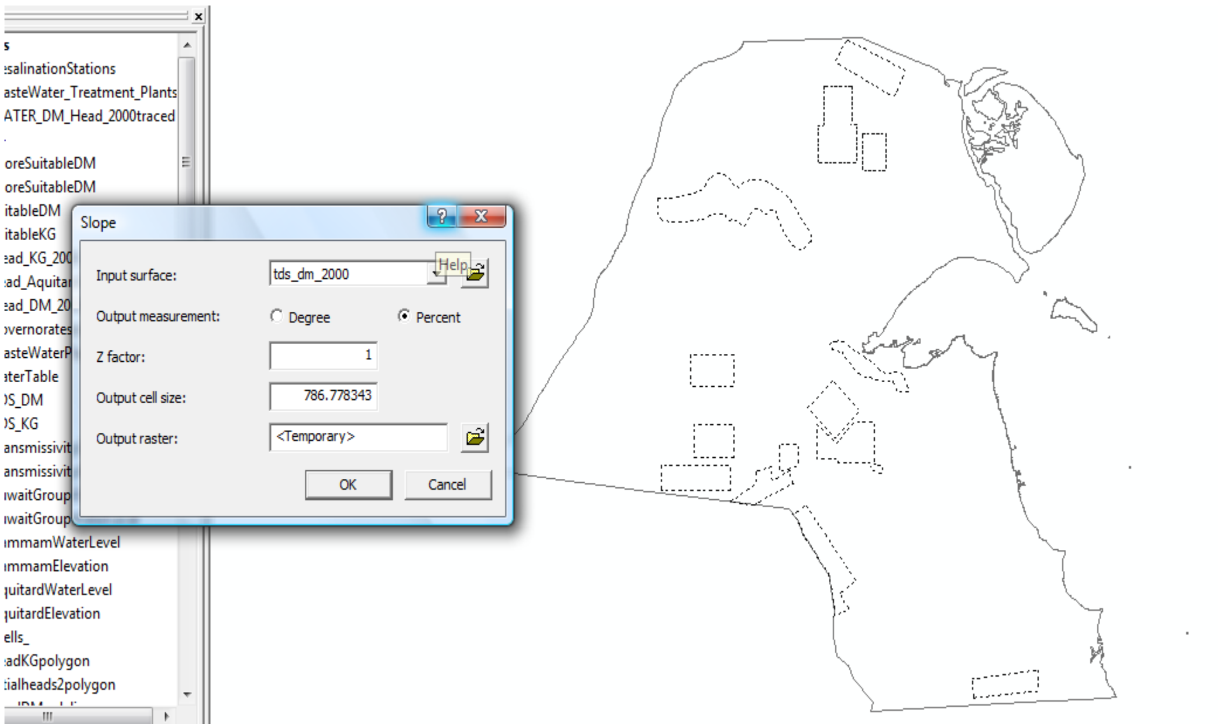


Figure 18 The Process for craetion Hydraulic Gradient (Slope) for Dammam Aquifer in ArcGIS

The salinity of groundwater in the Dammam Formation increases from 2500 mg/L in the southwest to more than 10,000 mg/L in the northeast (Senay et al., 1994). Lowering the TDS by mixing the injected water with native groundwater will increase the recovery efficiency and avoid buoyancy effects (Merritt, 1985). The ASR technique has to have the salinity of native groundwater as low as possible - less 5000 mg/L (Mukhopadhyay et al., 1992). While for selecting the suitable sites in Kuwait it is estimated that TDS should be less than 3500 mg/L in the target aquifer.

In ArcGIS it can find suitable sites for ASR operation based on the ASR criteria in Kuwait. A raster was created for transmissivity and TDS and used as input in Raster Calculator to find where the suitable sites are located for ASR in the Dammam aquifer with two other rasters, depth to water and hydraulic gradient. The general criteria are illustrated in Table (6) with the final criteria for selecting the most suitable site for ASR.

Table 6 General criteria for Selecting the most Suitable site

Parameter	**ASR criteria**	**Criteria for Grading the Suitable Sites**
Transmissivity	$150\ m^2/d \leq T \leq 1000\ m^2/d$	$200\ m^2/d \leq T \leq 400\ m^2/d$
Depth to water	$50\ m \leq D \leq 150\ m$	$50\ m \leq D \leq 90\ m$
Hydraulic gradient	$\Delta h \leq 0.27\ \%$	$\Delta h \leq 0.25\ \%$
TDS	$C \leq 5000$ mg/L	$C \leq 3500$ mg/L

The injected water that will be used in the ASR operation comes from the effluent of wastewater treatment plants with good quality, similar to that produced from desalination plants. Proximity of the source to the ASR operation is one of non-technical criteria that should be considered in selecting suitable ASR sites. Kuwait has four wastewater treatment plants; Sulibiya Station using an RO system to treated the wastewater is the best source of supply water for ASR wells. Another reason for choosing Sulibiya station, there is pipeline that goes out from the plant to provide treated wastewater for the farms in south of Kuwait. ASR facilities should be close to the populated area and a center for research, such as the KISR center or MEW station, to facilitate evaluation of the data during the injection and recovery operation. The ASR site should have restricted access to the field to avoid any potential contamination sources.

The objective of this stage was to identify suitable sites for ASR in the Dammam aquifer with grading starting from the most suitable to the most undesirable areas using the technical criteria in ArcGIS Spatial Analyst.

3.3. The Conceptual Design for ASR:

The volume of water that needs to be recovered from ASR storage is based on the source water availability, water demand and source water quality. First, form the time of requirement of the freshwater, the type of storage and the duration of recovery is determined. One of the ways to manage the freshwater demand and supply uses a comparison between the production and consumption and finds the months that the demand reaches the value of supply, or is close to it. The database of groundwater of Kuwait has feature classes for daily volume of freshwater demand and supply since 2001. Table X shows recent data for daily freshwater supply and demand in Kuwait. The difference between them is the daily volume of freshwater needed to meet the requirements in one month.

Table 7 daily freshwater supply and demand in Kuwait

Avg. Daily Production (Mm3/day)	Avg. Daily Consumption (Mm3/day)	Month. Year	ASR recovery	Volume needed (Mm3/day)
1.100	1.111	1.2005	Yes	-0.01
1.162	1.155	2.2005		0.00
1.205	1.212	3.2005		0.00
1.378	1.364	4.2005		0.01
1.444	1.459	5.2005	Yes	-0.01
1.525	1.531	6.2005	Yes	-0.01
1.525	1.537	7.2005	Yes	-0.01
1.529	1.543	8.2005	Yes	-0.01
1.538	1.538	9.2005		0.000
1.530	1.514	10.2005		0.01
1.424	1.381	11.2005		0.044
1.293	1.305	12.2005	Yes	-0.01

The months that need more supply from ASR operation to sustain the production from the desalination plants to meet the demand are January, May, June, July, August and December. In Kuwait, January and December are winter months (season starts from November and extends till February) and they can meet the daily demand from surface storage or increase the capacity of production in one of the desalination plant units. Based on the requirement of ASR recovery, the type of subsurface storage is seasonal storage and the mechanism for injection and recovery is cyclical which helps to control the head level and build the buffer zone around the subsurface storage.

The second step is identifying the recovery operation parameters which include the amount of water needed in critical situation and the time of the recovery cycles that should occur in the summer months. The Target Storage Volume (TSV) is defined as the total volume of water injected in subsurface storage zone and the buffer zone (Pyne, 2005) which is needed to build up the buffer zone before starting the actual cycles to create the TSV. Prior to the actual implementation of ASR operation, many cycles of injection and recovery must take place to determine the buffer zone and keep the native groundwater away from the storage zone. The prior cycles are just a one-time investment volume of water in injection and recovery cycles for creating buffer zone. The time to create the buffer zone is estimated to be a year due to the high TDS value in the groundwater of Kuwait with short prior cycles before the actual cycles of ASR operation. The rate of injected water in the prior cycles is assumed equal to or higher than the rate of recovery in the actual ASR cycles (Pyne, 1995).

One of the benefits of the ASR technique is that it needs a small surface area for implementation. Eight ASR wells are a good starting point for ASR operations and they do not occupy a large area. Based on Table X illustrating demand exceeding supply in the summer season, the recovery cycle of the ASR operation will produce for three months each year starting in June and stopping at the end of August and the total daily recovery volume from these 8 ASR wells is 100000 m^3. On the other hand, the injection cycle in

ASR operation is estimated to start after the end of the last recovery cycle to build the buffer zone. With lowering the daily rate of injection in ASR cycles to 550 m^3/d per well, which is less than half of the daily rate of recovery per well, the duration of injection in each ASR cycle is 9 months. The daily rate of injection in buffer zone cycles is 1500 m^3/d per well, which is slightly more than the rate of recovery per well to leave a small volume for improvement of the water quality, the daily rate of prior cycles is 250 m^3/s per well. Three prior cycles are implemented to build the buffer zone including 3 months of injection and 1 month of recovery.

The Recovery Efficiency percentage is controlled by two criteria, the recovery volume in ASR operation cycles and the TDS value, to reach the desirable limit of 70%. The recovery volume is 100000 m^3 per day for 3 months while the production should be stopped when a TDS value of 1500 mg/L is reached, that is the standard of drinkable freshwater in Kuwait. The recovery efficiency is affected by the well arrangement in the ASR field, which should minimize the mixing between the stored and the native water. In numerical modeling, 10 runs were made with different well arrangements of 8 ASR wells. This is an example of some of the alternative ASR well arrangements that will be used in next stage. The well spacing is determined by finding the theoretical radius of TSV (Pyne, 2005) which is estimated in this case to be between 200 and 400 m.

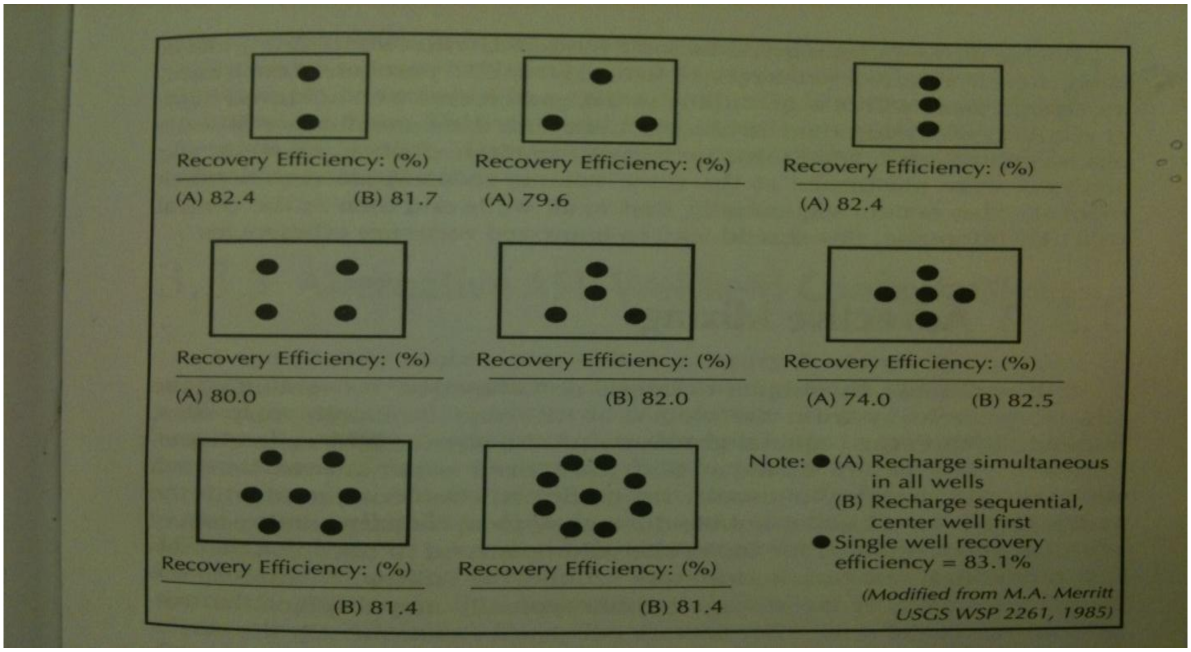


Figure 19 Types of Distribution of ASR Wells (Source: Pyne, 2005)

3.4. Numerical Modeling of ASR operation:

The previous three stages prepared the hydrogeologic data in GIS format and designed the required daily volume of water for the ASR injection and recovery operation at suitable sites. Groundwater Vistas software was used to evaluate the hydraulic effects of injection and recovery operation on the Dammam aquifer under certain conditions. Also, it helps to select the ASR operating scenario that gives the optimum recovery efficiency and improvement for groundwater under ASR cycles by assigning monitoring wells. The approach of this stage is creating a strategic reserve of freshwater in the Dammam aquifer as a seasonal storage. Before setting up the ASR operation, the prior cycles to creating the buffer zone start with 3 months of injection operation (1500 m^3/d for each well) followed by recovery for 1 month (250 m^3/d for each well) continuously in the same manner for one year. For three years the ASR cycles are implemented with 9 months injection of 550 m^3/d for each well and the total daily recovery volume is 1250 m^3/d per well with TDS less than 1500 mg/L during 3 months.

3.4.1. Groundwater Vistas software:

Groundwater Vistas (GV) is developed by ModelCad (Citation: Environmental Simulations, Inc, 1998). It is a unique groundwater modeling environment for Microsoft Windows that combines powerful finite-difference groundwater models with comprehensive graphical analysis tools. It can display the model in both plan and cross-sectional view. GV is designed to be an independent modeling system and supports many groundwater models such as MODFLOW, MODPATH, MT3D, etc. Also, it is easy for the user familiar with different software making it possible to import and export hydraulic data from Surfer and ArcGIS software. Also, it can import maps from ArcGIS, such as the location of the aquifers, transportation map and the political map. GV imports a wide variety of files such as MODFLOW data sets, boundary condition data and aquifer property data. The results can be displayed in both plan and cross-sectional windows as contours or color flood for the water head and the concentration.

3.4.2. The Model Design:

For this study, the model design has 2 aquifers (the Kuwait Group and the Dammam Formation) that are separated by an aquitard layer (Omar et al., 1981). The aquitard is firmed from a clay layer at the lower part of the Kuwait Group and a chert layer at the top of the Dammam Formation. The surface area for whole the model is 20 km by 20 km with the origin point at (750,000 m, 3210,000 m) in Universal Transverse Mercator coordinates. The modeled surface area is divided into a grid of 50 by 50 cells in each of three layers. The grid spacing varies in the model being large near the border and decreasing until it reaches the selected suitable ASR area with a grid spacing 100 m in the center of the ASR field and 125 m surrounding it to provide a more accurate modeled value. Raster layers were created in the first stage for the database of groundwater Kuwait; they are converted to shapfiles in ArcGIS to use them as input for initial heads, initial concentration, top elevation, bottom elevation and hydraulic conductivity for each layer of the model in the property files in GV. The constant head/concentration in the boundary conditions (BCs) file is assigned to the boundary cells of the model in all three layers, where the water heads and TDS concentration were held constant for the simulation period. Some of hydraulic parameter properties for the model are based on many past studies for the groundwater of Kuwait shown in Table (8) below (Mukhopadhyay et al., 1994; Mukhopadhyay and Al-Otaibi, 2002).

Table 8 Hydraulic Parameters of Kuwait Aquifer Group and Dammam aquifer

Parameter	Kuwait Group Aquifer	Aquitard	Dammam Aquifer
Specific storage/ Specific yield	1.8×10^{-4}/ 0.18	1.8×10^{-4}	5×10^{-6}
Porosity	0.20	0.05	0.05
Transverse Dispersivity (m)	0.1	0.1	1
Longitudinal Dispersivity (m)	1	1	10

Using the criteria explained above, the most suitable area for ASR operation has been selected (using ArcGIS tools) and it occupies almost 2.5 km by 4 km, while the ASR field needs a small area for operation based on the well arrangement and the spacing between wells. Ten runs were made with different designs for the ASR wells have implemented to get the optimum recovery efficiency to meet the demand from June until August and create a strategic reserve of drinkable water in Dammam aquifer.

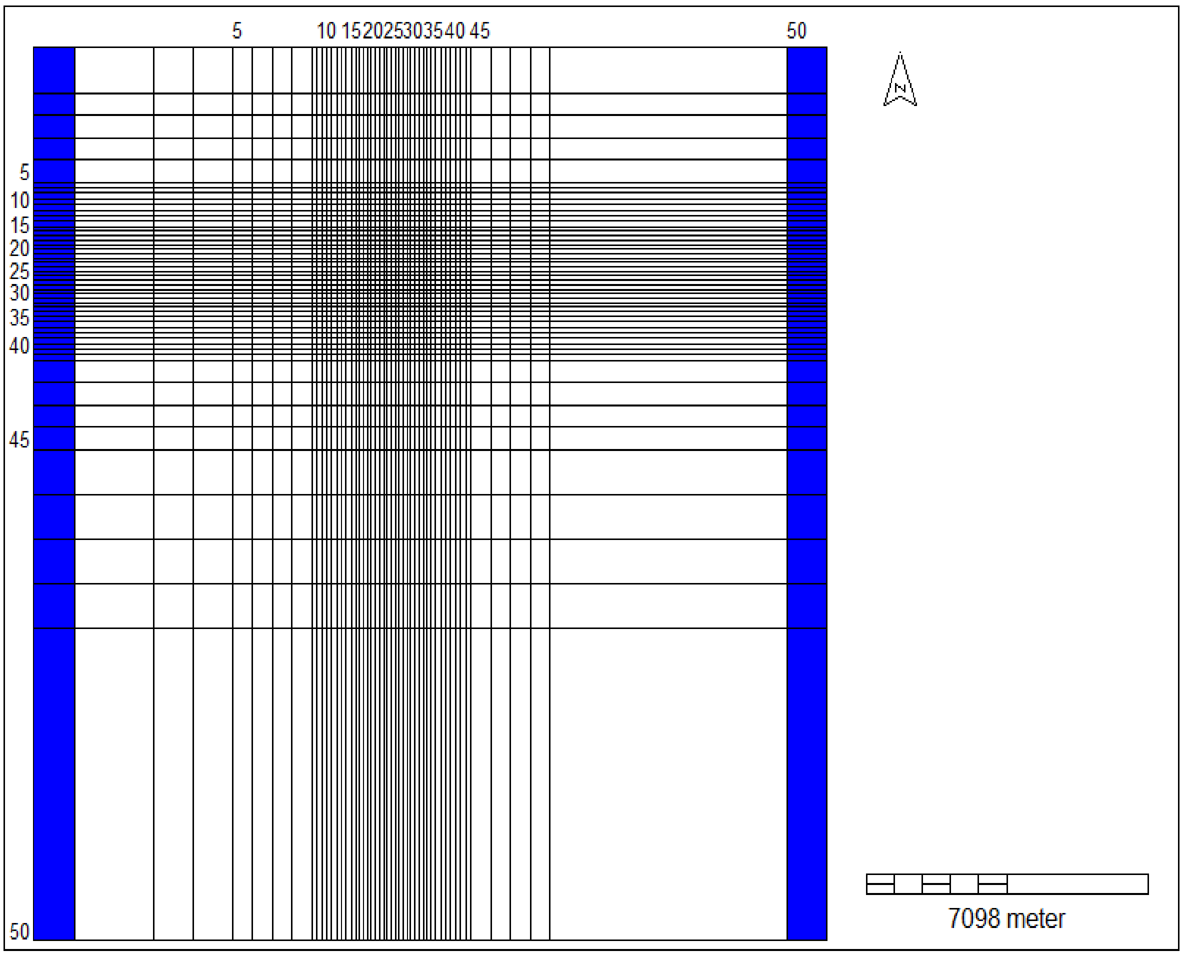


Figure 20 The modeling grid Design in GV software

3.4.3. ASR Operation:

All of the runs were carried in GV following the same procedure except the last two run included 10 wells (instead of 8 in the previous runs). The wells in the center (red wells in Fig. 21) work for injecting drinkable water during all stress periods while the ASR wells located around the center (black wells in Fig. 21) start operation (after one year with 3 prior cycles) each injecting for 9 months (4400 m^3/d) followed by recovery for 3 months (1000 m^3/d).

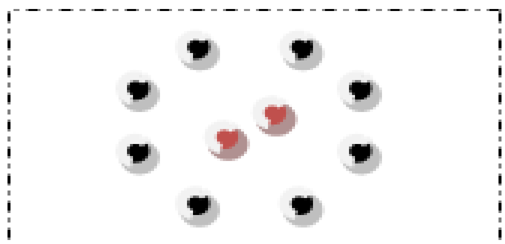


Figure 21 the mechanism of Run 9 and 10

The wells spacing and arrangement of ASR wells criteria were considered in the first eight runs to achieve the desirable recovery volume with the TDS limit of 1500 mg/L. All runs started with prior cycles to create the transition zone between the stored and native water. The daily demand requirement must be met daily from 8 wells within the ASR field area in the summer time and the injection starts after the prior cycles end. MODFLOW is used to find effect of injection and recovery during the simulation while MT3D is used to find the TDS concentration during the ASR operation.

The Coordinate:

Well 1	Row 32	Col 21
Well 2	Row 34	Col 18
Well 3	Row 34	Col 21
Well 4	Row 34	Col 24
Well 5	Row 35	Col 18
Well 6	Row 35	Col 21
Well 7	Row 35	Col 24
Well 8	Row 36	Col 21

The Horizontal spacing between (2,3 and 4) and (5,6 and 7) from each well center is 375 m

The vertical spacing between 1 and 3 from each well center is 212.5 m

The vertical spacing between (2 and 5), (3,6 and 8) and (4 and 7) from each well center is 100 m

Run 1

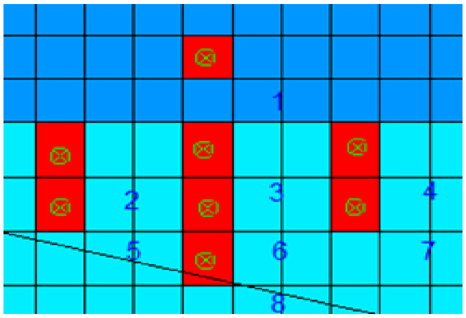


Figure 22 Location of ASR Wells in Run 1

The Coordinate:

Well 1	Row 24	Col 33
Well 2	Row 24	Col 35
Well 3	Row 24	Col 37
Well 4	Row 26	Col 33
Well 5	Row 26	Col 37
Well 6	Row 28	Col 33
Well 7	Row 28	Col 35
Well 8	Row 28	Col 37

The Horizontal spacing between (1,2 and 3) and (6,7 and 8) from each well center is 200 m

The vertical spacing between (1,4 and 6) and (3,5 and 8)from each well center is 200 m.

Run 2

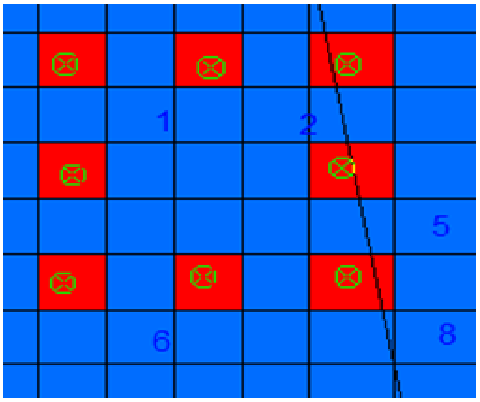
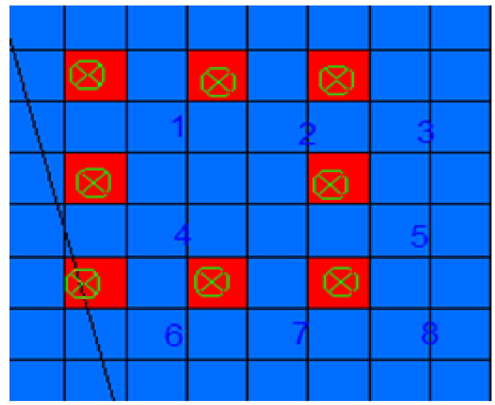


Figure 23 Location of ASR Wells in Run 2

The Coordinate: **Run 3**

Well 1	Row 24	Col 29
Well 2	Row 24	Col 31
Well 3	Row 24	Col 33
Well 4	Row 26	Col 29
Well 5	Row 26	Col 33
Well 6	Row 28	Col 29
Well 7	Row 28	Col 31
Well 8	Row 28	Col 33



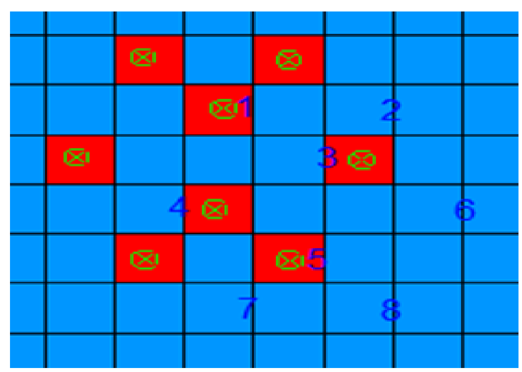
The Horizontal spacing between (1,2 and 3) and (6,7 and 8) from each well center is 200 m

The vertical spacing between (1, 4 and 6) and (3, 5 and 8) from each well center is 200 m.

Figure 24 Location of ASR Wells in Run 3

The Coordinate: **Run 4**

Well 1	Row 26	Col 19
Well 2	Row 26	Col 21
Well 3	Row 27	Col 20
Well 4	Row 28	Col 18
Well 5	Row 28	Col 22
Well 6	Row 29	Col 20
Well 7	Row 30	Col 19
Well 8	Row 30	Col 21



The Horizontal spacing between (1 and 2) and (7 and 8) from each well center is 200 m

The Horizontal spacing between (4 and 6) from each well center is 400 m

The vertical spacing between (1 and 7) and (2 and 8) from each well center is 400 m.

The vertical spacing between (3 and 5) from each well center is 200 m.

Figure 25 Location of ASR Wells in Run 4

The Coordinate: **Run 5**

Well 1	Row 36	Col 18	Grid size 100x125
Well 2	Row 32	Col 18	Grid size 100x100
Well 3	Row 36	Col 23	Grid size 100x125
Well 4	Row 32	Col 23	Grid size 100x100
Well 5	Row 35	Col 16	Grid size 125x125
Well 6	Row 32	Col 28	Grid size 100x100
Well 7	Row 35	Col 26	Grid size 100x125
Well 8	Row 32	Col 33	Grid size 100x100

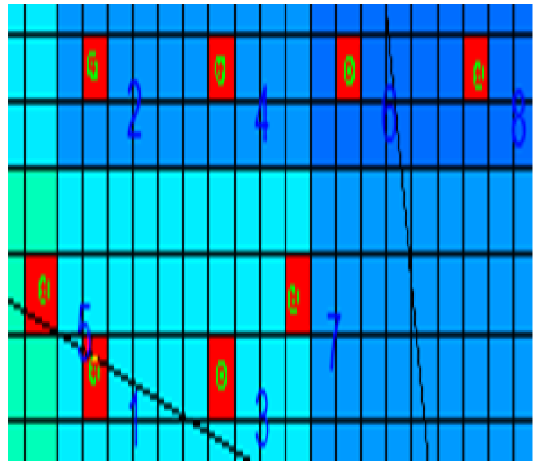
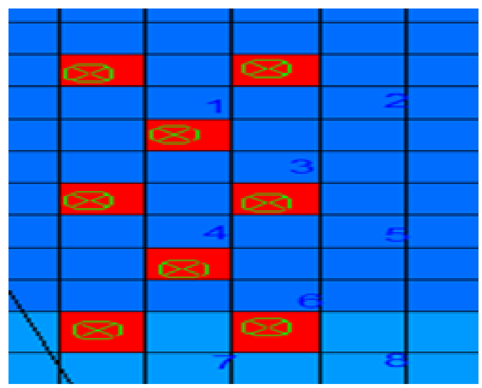


Figure 26 Location of ASR Wells in Run 5

The Coordinate: **Run 6**

Well 1	Row 26	Col 31
Well 2	Row 26	Col 33
Well 3	Row 28	Col 32
Well 4	Row 30	Col 31
Well 5	Row 30	Col 33
Well 6	Row 32	Col 32
Well 7	Row 34	Col 31
Well 8	Row 34	Col 33



The Horizontal spacing between (1 and 2), (4 and 5) and (7 and 8) from each well center is 200 m

The vertical spacing between (1 and 4),(2 and 5) and (3 and 6) from each well center is 400 m

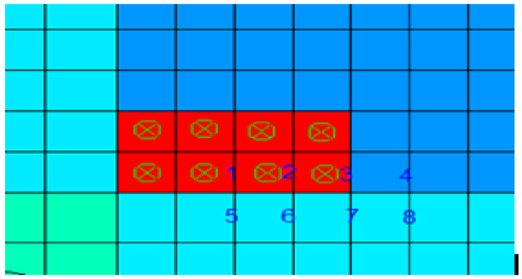
The vertical spacing between (4 and 7) and (5 and 8) from each well center is 412.5 m.

Figure 27 Location of ASR Wells in Run 6

The Coordinate:

Well 1	Row 32	Col 17
Well 2	Row 32	Col 18
Well 3	Row 32	Col 19
Well 4	Row 32	Col 20
Well 5	Row 33	Col 17
Well 6	Row 33	Col 18
Well 7	Row 33	Col 19
Well 8	Row 33	Col 20

Run 7



The Horizontal spacing between (1, 2, 3 and 4) and (5, 6, 7 and 8) from each well center is 100 m.

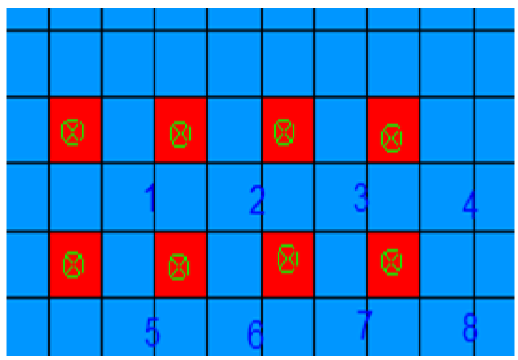
The vertical spacing between (1 and 5), (2 and 6), (3 and 7) and (4 and 8) from each well center is 100 m.

Figure 28 Location of ASR Wells in Run 7

The Coordinate:

Well 1	Row 30	Col 18
Well 2	Row 30	Col 20
Well 3	Row 30	Col 22
Well 4	Row 30	Col 24
Well 5	Row 32	Col 18
Well 6	Row 32	Col 20
Well 7	Row 32	Col 22
Well 8	Row 32	Col 24

Run 8



The Horizontal spacing between (1, 2, 3 and 4) and (5, 6, 7 and 8) from each well center is 200 m.

The vertical spacing between (1 and 5), (2 and 6), (3 and 7) and (4 and 8) from each well center is 200 m.

Figure 29 Location of ASR Wells in Run 8

The Coordinate:

Well 1	Row 29	Col 19	Grid size 100x100
Well 2	Row 29	Col 21	Grid size 100x100
Well 3	Row 30	Col 18	Grid size 100x100
Well 4	Row 30	Col 22	Grid size 100x100
Well 5	Row 32	Col 18	Grid size 100x100
Well 6	Row 32	Col 22	Grid size 100x100
Well 7	Row 33	Col 19	Grid size 100x100
Well 8	Row 33	Col 21	Grid size 100x100
Well 9	Row 31	Col 19	Grid size 100x100
Well 10	Row 31	Col 21	Grid size 100x100

Run 9

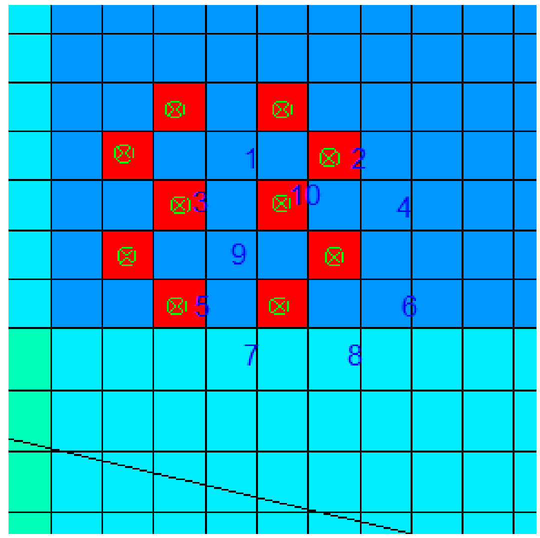


Figure 30 Location of ASR Wells in Run 9*

The Coordinate:

Well 1	Row 29	Col 28	Grid size 100x100
Well 2	Row 29	Col 30	Grid size 100x100
Well 3	Row 30	Col 27	Grid size 100x100
Well 4	Row 30	Col 31	Grid size 100x100
Well 5	Row 32	Col 27	Grid size 100x100
Well 6	Row 32	Col 31	Grid size 100x100
Well 7	Row 33	Col 28	Grid size 100x100
Well 8	Row 33	Col 30	Grid size 100x100
Well 9	Row 30	Col 29	Grid size 100x100
Well 10	Row 32	Col 29	Grid size 100x100

Run 10

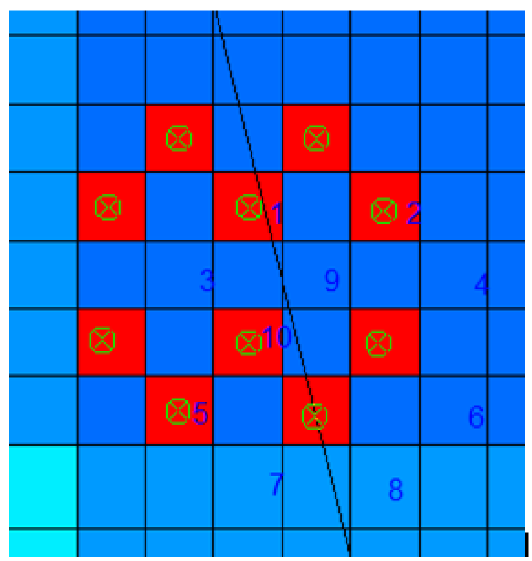


Figure 31 Location of ASR Wells in Run 10*

*wells 9 and 10 are operating as injection wells for 1464 days with constant daily rate 550 per well. After one year from operating Wells 9 and 10, the ASR wells operating as cycles for 3 years (1 cycle = 9 months injection, 3 months recovery)

CHAPTER 4: Results and Discussion

This chapter describes and discusses the results of converting hydrogeological data, and information related to the productivity of water resources and demand into feature classes which were created for the GIS database of groundwater of Kuwait. Also, the results obtained from applying the ASR technique, starting with determining the volume of water needed to meet the demand and the suitable sites for ASR and ending with the different ways of applying ASR within the selected area. Groundwater Vistas software used in 10 different runs for designing the ASR technique for different sites within the selected ASR area in Kuwait to determine the optimum operating conditions based on the arrangement of wells, spacing between them, ASR field location, volume of injected water, hydraulic effects and recovery efficiency.

First, all the hydrogelogic data maps, the data of supply and demand have been transferred to ArcGIS as feature classes in the geodatabase called GwKuwait. It contains all of the data of groundwater of Kuwait which makes it convenient to make a comparison between any two features. Then, based on the ASR site selection criteria for suitable sites for applying ASR technique, ArcGIS tools produced a raster of suitable sites classifying them with graded scores (grade 4 being the most suitable). The results of the ASR technique design stage included the volume of water need for injection and pumping as a recovery volume, characteristics of the ASR field (spacing between wells and the arrangement) and identifying how many cycles are needed before and during implementing of the ASR operation. All of hydraulic data was imported into Groundwater Vistas form the ArcView Shapefiles from which the design model was built with three layers. The numerical modeling runs simulated 10 different ways for the ASR concept for several cycles, both prior cycles and main cycles. Each well's recovery volume was compared to the desired volume to evaluate the recovery efficiency and identify the target storage volume in the Dammam aquifer.

4.1. Database (Groundwater of Kuwait)

In ArcView, point features represent the location of desalination plants and wastewater treatments plants in Kuwait that have the productions and the installed capacity from each plant over the last years in their attributes table . The groundwater aquifers are represented by polygon features, with areas defined based on the limitation from the Ministry of Electricity and Water, which have the production capacity for each field in their attributes table. In addition, a new feature class has been created for the Kuwait map (polygon) with the total production (Mm^3per year), consumption (Mm^3per year), consumption per capita (L/c/day) and surface storage (Mm^3 per year) between the period 1980 and 2007 in its attributes table.

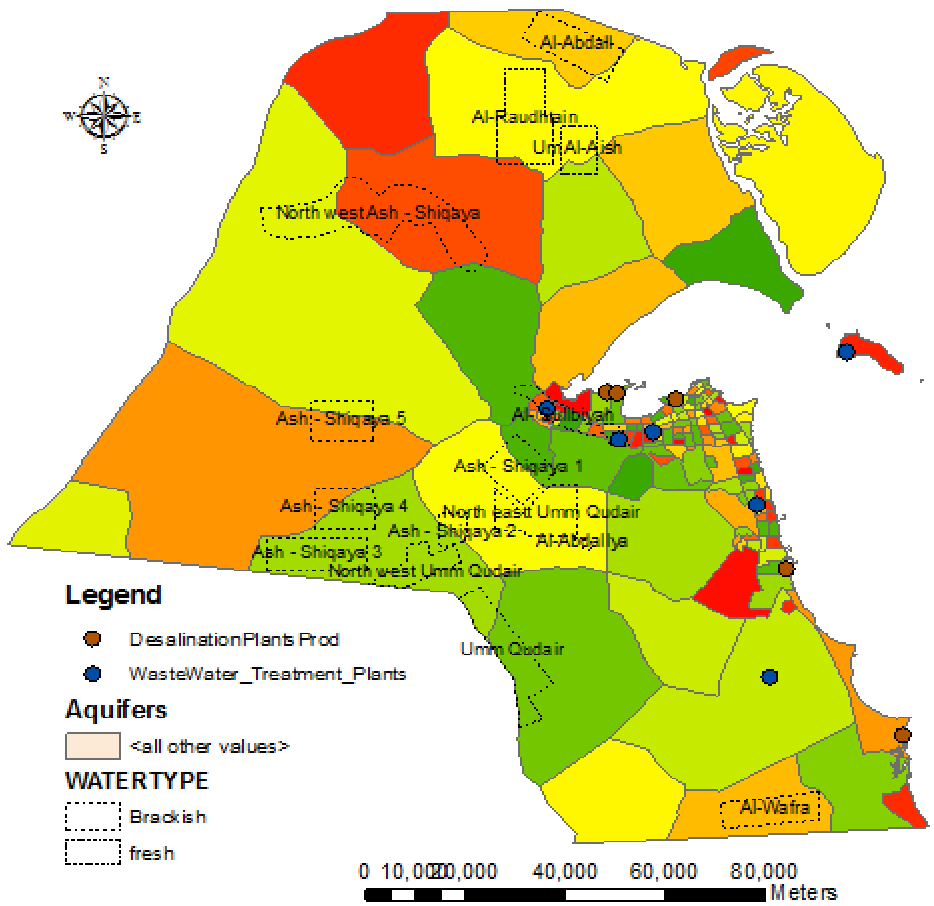


Figure 32 Location of Desalination Plants, Wastewater Treatment Plants and Groundwater Fields

ArcGIS tools played a significant role in transferring all of the hydraulic parameters of groundwater of Kuwait from the original data to inputs in numerical modeling. For instance, Fig. X shows the original data map for head level in the Dammam aquifer (Citation: KISR, 2009) while Fig. X shows the raster map in ArcView after it was created from polylines. The raster map for the water head in the Dammam aquifer gives an accurate value in the raster with a cell size of 785 m by 785 m and the number of rows and columns are 236 and 223, respectively.

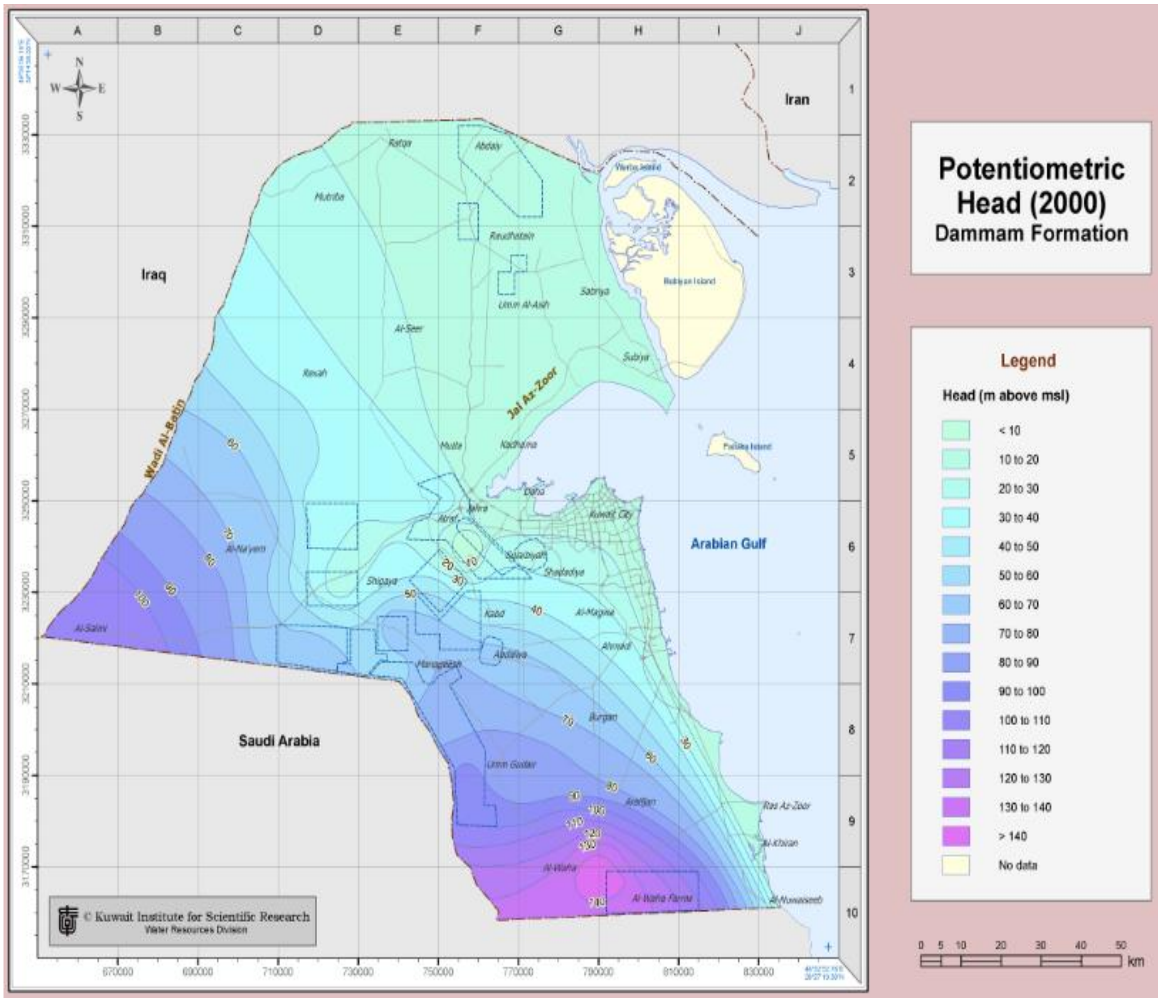


Figure 33 Potentiometric Head of Dammam Aquifer (Source:KISR, 2009)

The value of all hydraulic parameters in the raster data can be updated, which cannot be done in the original map document. The ArcGIS Raster Calculator can find the difference in the updated and prior raster (e.g., decline or rise in head level).

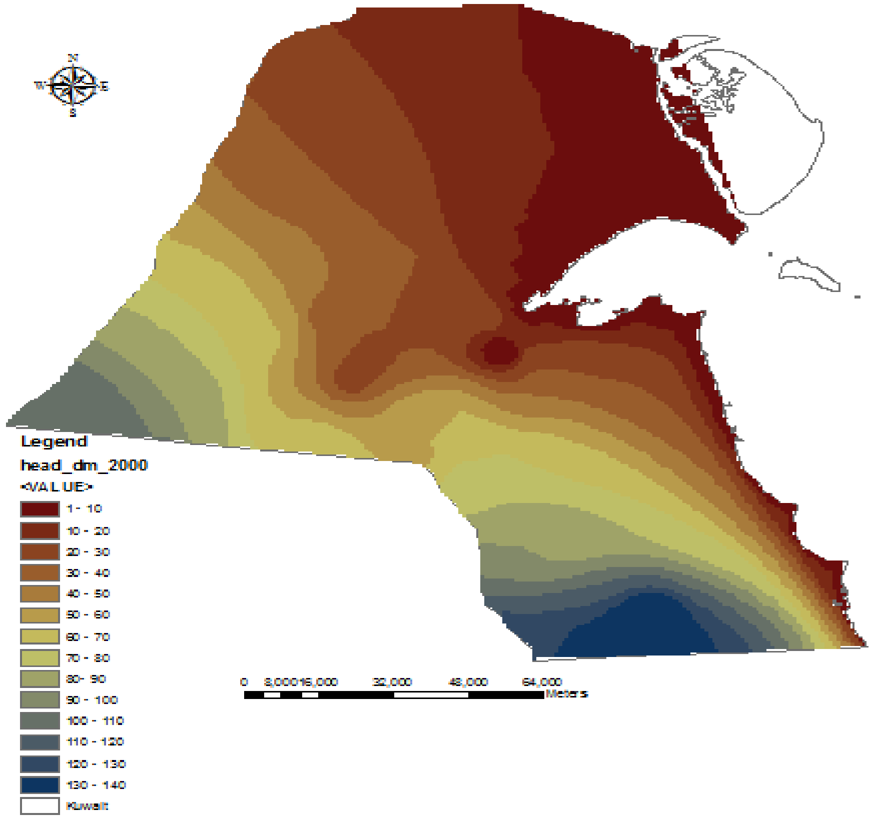


Figure 34 Potentiometric Head of Dammam Aquifer in ArcGIS

Figure 35 shows the geodatabase of water resources of Kuwait and has four main feature datasets and rasters (TDS, transmissivity, head, aquifer thickness, top elevation of aquifer, and hydraulic gradient). The feature datasets are background, data, Kuwait, and production and demand.

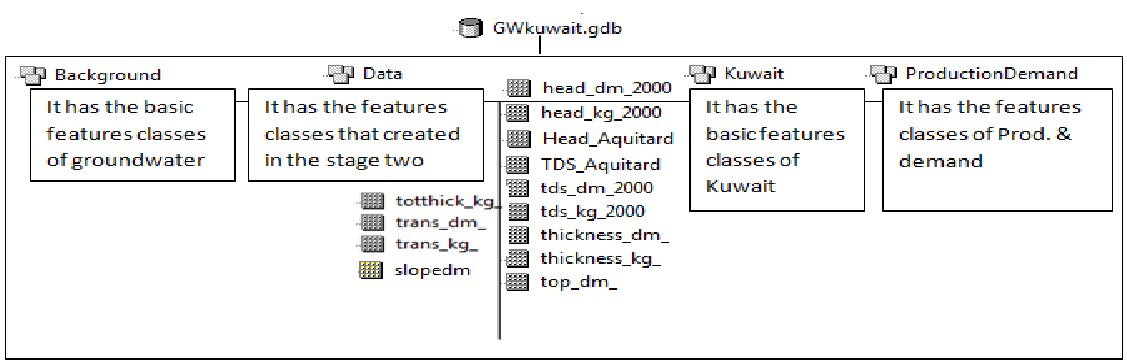


Figure 35 Geodatabase of Water Resource of Kuwait

4.2. Selecting suitable sites for ASR operation

The criteria for selecting suitable sites for ASR operation are based on hydrogeology factors and the distance to source water supplies for injection. These criteria were used to delineate sites where the Dammam aquifer has the suitable combination of hydrogeological factors and the non-technical factors (close to power plant, water supply and populated areas).

The ArcGIS Raster Calculator used raster data from the database of groundwater of Kuwait as input to find suitable sites for ASR operation. The Raster Calculator is shown in Figure 36.

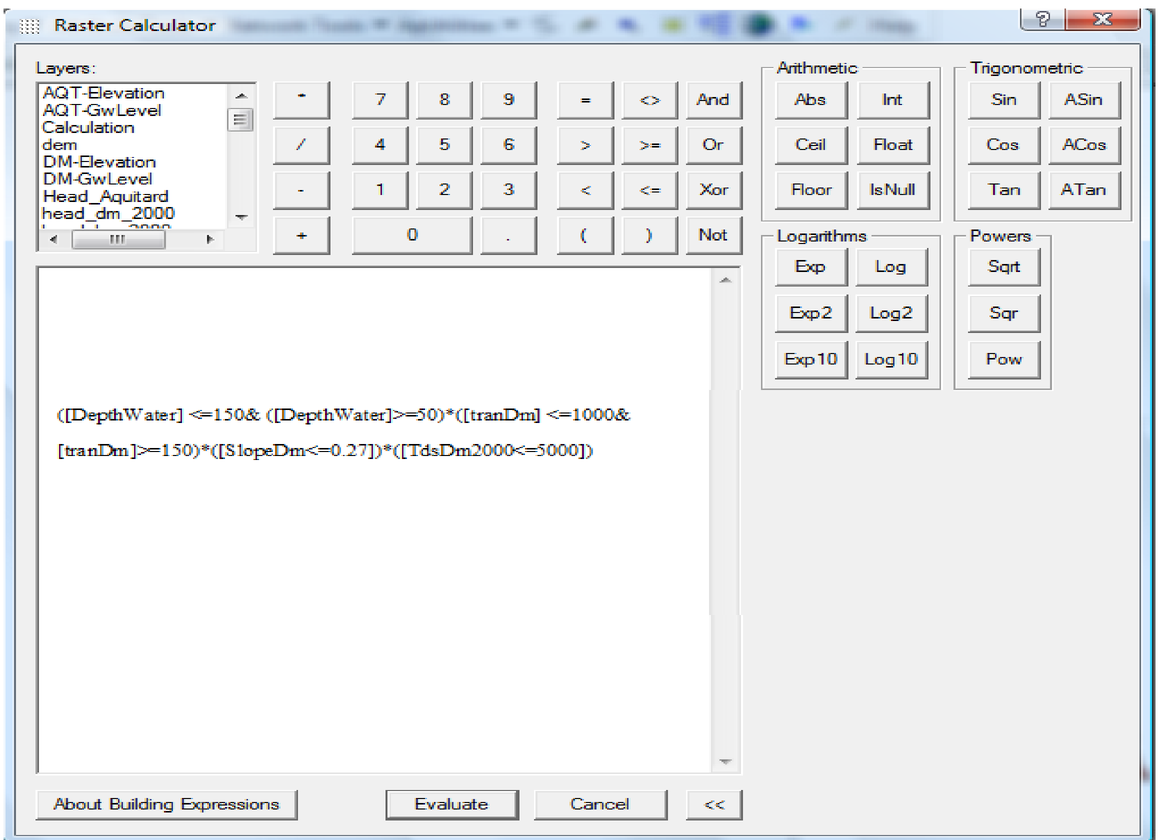


Figure 36 The Input Equation to find Suitable Site in Raster Calculator

The selected suitable sites in the Dammam aquifer are highlighted in blue in Figure 37. Using the grading method the most suitable site for ASR operation, grades were found by multiply the suitable raster data by the following equation indicating the degree to which the site matches the selection criteria for grading.

{([DepthWater] <= 90 & [DepthWater] >= 50) + ([tranDm] <= 400& [tranDm]>= 200) + ([SlopeDm] <= 0.25) + ([TdsDm2000] <= 3500)}

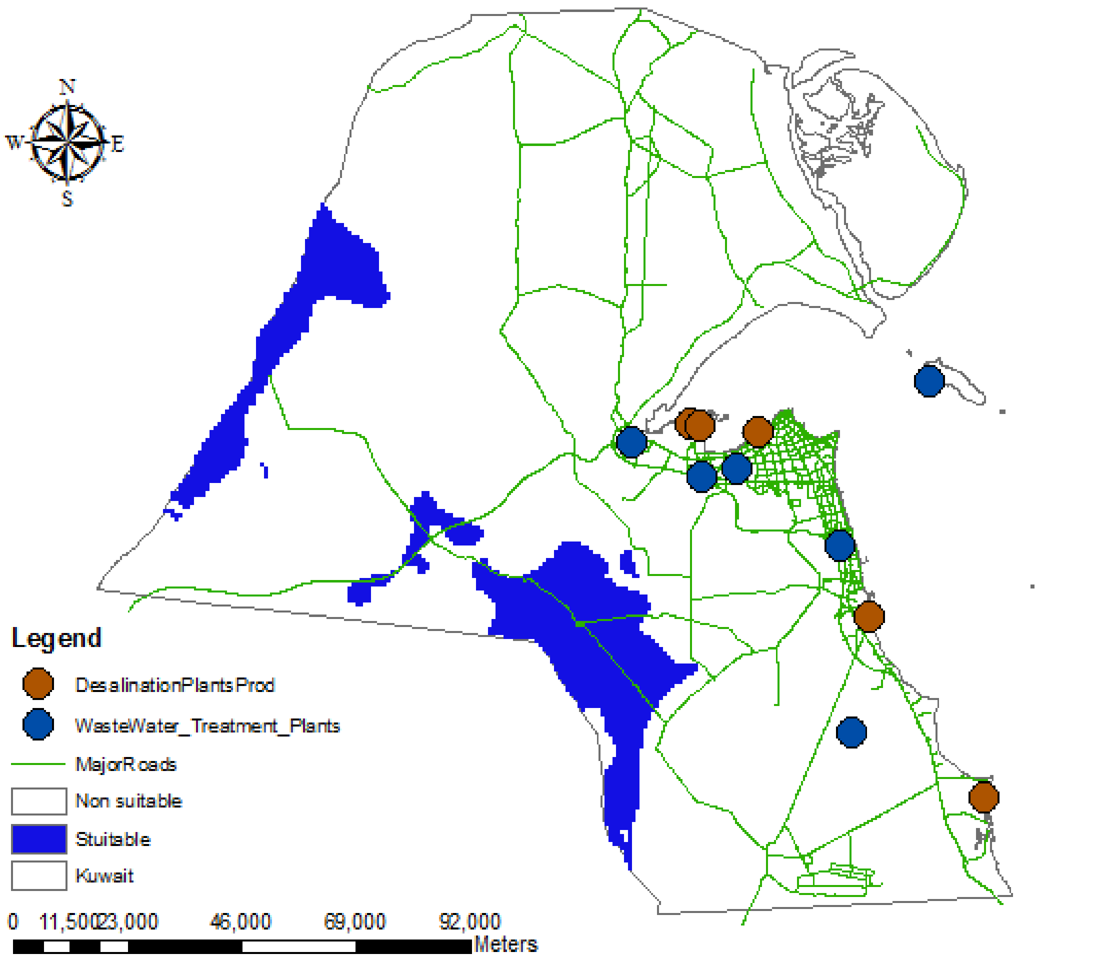


Figure 37 the Suitable Sites for ASR Operation in Kuwait

In Figure 38, the suitability scale graded areas are shown from the least suitable to the most suitable for ASR operation. However the other non-technical factors like nearness from major roads, distance from water source for injection phase and distance from populated areas are taken into account in selecting the best site for ASR operation and this is highlighted in a red circle. The surface area of the selected suitable site is 3152 m by 4000 m, which is a small area and this is one of the benefits of ASR technique.

Sulibya wastewater treatment plant is the best water source to supply the ASR field with water of sufficiently high quality for the injection phase for different reasons. First, the total currently utilized is about 30%, so the rest is available for use in the injection operation. Another reason is that the Sulibya wastewater treatment plant is producing water that is as good in quality as desalinated water. The distance of the major road from the selected ASR site that is 500 m with no groundwater pollution potential or oil field nearby.

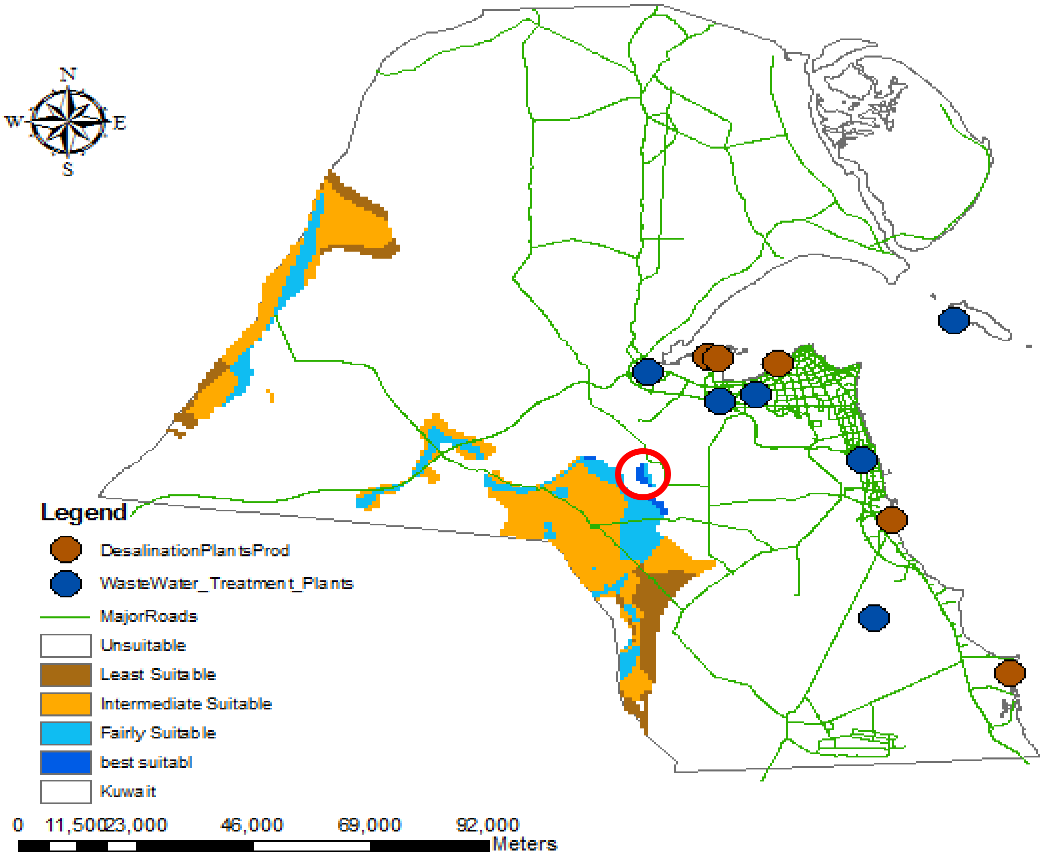


Figure 38 suitability scale graded sites

The selected ASR field is located in the most suitable area and fairly suitable area and its hydraulic parameters are optimum for ASR operation in the Dammam aquifer.

Table 9 Hydraulic Properties of Selected site

Hydraulic Parameter	The range of optimum value
Hydraulic conductivity (Kx)	between 1 m/day to 2 m/d
Hydraulic conductivity (Kz)	Between 0.1 m/d to 0.2 m/d
TDS	3000 mg / L- 3111 mg / L
Head level	Between 50m and 52m (amsl)

4.3. ASR Operation Design

Two scenarios are considered for applying ASR technique in Kuwait. The first scenario was has two phases; the first phase (prior cycles) creates the buffer zone between the storage zone and the native groundwater (which has a high TDS value). The second phase, called the basic ASR cycles, is designed to provide consumers the required volume of water after each injection phase and uses subsurface storage for emergency conditions. There is not any inactive period between the injection and recovery cycle in both phases to increase the recovery efficiency for the basic cycle. The volume of water in the recovery phase is based on the difference between the demand and the production of freshwater in the period 2001 and 2005 (MEW, 2006). The optimum value for the spacing between wells was between 100 and 450 m. Table X shows the duration and volume of water for each cycle in the ASR operation.

In the second scenario water was injected into the aquifer for four years by two wells with constant injection rates. Then, ASR basic cycles started after one year from the beginning of project. The wells in this scenario were arranged with two injection wells in the middle of the ASR field and eight extraction wells in a circle on the border. The approach of this scenario, creating a circle in ASR field, has good water quality in the middle.

Table 10 The mechanism of Fist Scenario

Phase	Type of cycle	Duration	The daily Volume of water per well
Prior cycles	Injection	92 days	1500 m^3
	Recovery	30 days	-250* m^3
	Injection	92 days	1500 m^3
	Recovery	30 days	-250* m^3
	Injection	92 days	1500 m^3
	Recovery	30 days	-250* m^3
First cycle	Injection	273 days	550 m^3
	Recovery	93 days	-1250* m^3
Second cycle	Injection	273 days	550 m^3
	Recovery	93 days	-1250* m^3
Third cycle	Injection	273 days	550 m^3
	Recovery	93 days	-1250* m^3

*negative sign means this volume is pump out from the well.

Table 11 The Mechanism of Second Scenario

Phase	Type of cycle	Duration	The daily Volume of water per well
Injection cycle*	Injection	1464 days	550 m^3
First cycle**	Injection	273 days	550 m^3
	Recovery	93 days	-1250* m^3
Second cycle	Injection	273 days	550 m^3
	Recovery	93 days	-1250* m^3
Third cycle	Injection	273 days	550 m^3
	Recovery	93 days	-1250* m^3

*this cycle is a continuous injection cycle which starts from the beginning of the project and ends with the last cycle in this scenario.
**this cycle starts after one a year from the beginning of injection cycle.

4.4. Numerical Modeling Results

Two scenarios were selected for the ASR technique at the desired site. The first 8 runs in Groundwater Vistas follow the first scenario with different locations of wells within the site, spacing between the wells and the arrangement of wells. The reasons for the diversity between them were to determine the best design to maximize the recovery efficiency and the size of subsurface storage with good water quality. Runs 9 and 10 were applied to the second scenario where different location of wells and distribution of wells were examined. These 10 runs evaluated the possible impact to the potentiometric head and determined the engineering feasibility of the injection phase and provided water quality and volume information that are needed to determine the recovery efficiency.

4.4.1. First Scenario (Run 1):

This run simulated the injection and recovery phases for 8 wells in the southwest most suitable site. The horizontal hydraulic conductivity was 2.027 m/d for all of wells except well number 1 was 1.351 m per day while the initial vertical hydraulic conductivity was one-tenth of the horizontal hydraulic conductivity in the ASR field. The horizontal spacing between all wells was 300 m from center to center. The head and TDS concentration in the Dammam aquifer were assigned to be the starting values for the run (initial head and initial concentration values imported from the groundwater database as shapfiles). Fig. 39 shows the location of the wells (ASR field) in the GV software.

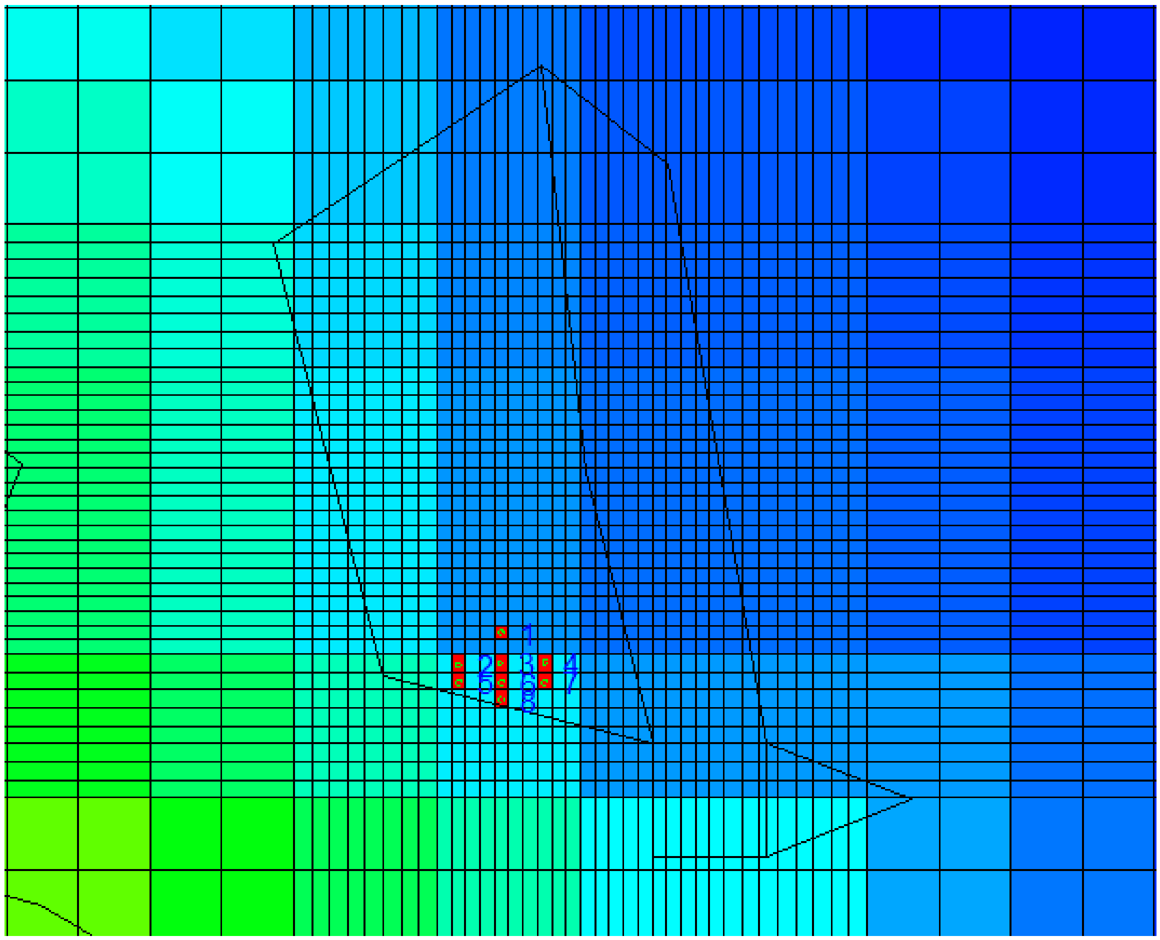


Figure 39 Location of ASR wells in Run 1

The resulting water head and TDS concentration for each time step were obtained from MODFLOW and MT3D. MODFLOW simulated the head with respect to the injection and recovery phases. Then, MT3D used the head output from MODFLOW with initial TDS concentrations as input and simulated the TDS during the ASR operation. A monitoring well was located close to each ASR well to measure the rise and decline of head and concentration. The hydrograph illustrates the head level and concentration over the duration of scenario one for each monitoring well.

Figures 40 and 41 show the resulting head contours after the prior cycles (one year) and after the end of first basic cycle (2 years). The head level dropped down dramatically when the recovery cycles were operating.

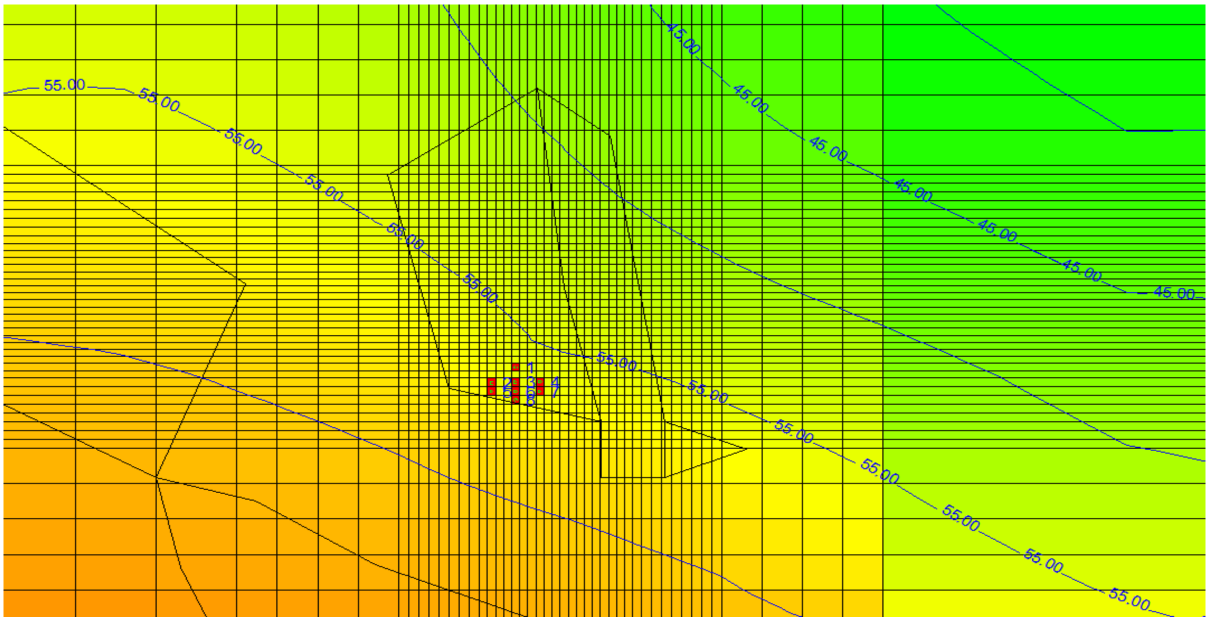


Figure 40 Head Countours after the end of Prior Cycles

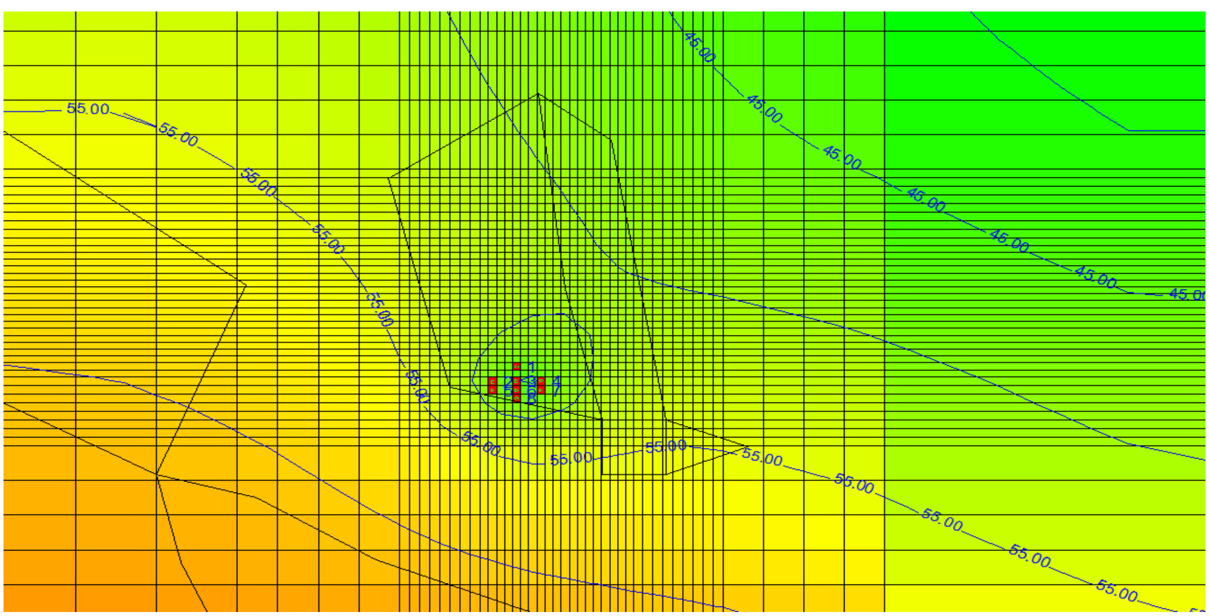


Figure 41 Head Contours after the end of First Basic Cycle

The hydrograph for ASR well number 1 showed that the head level fluctuated starting at 58 m (amsl) and reached 44 m (amsl) at the end of the last cycle.

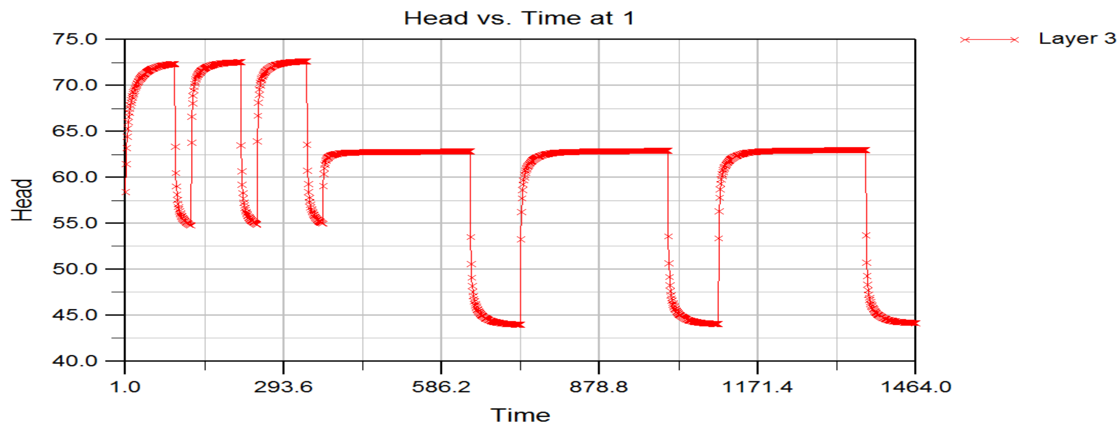


Figure 42 Hydrograph of Head for ASR well 1 (Run 1)

It was assumed that the allowable limits for head level rise and decline is 20 m above and below the initial value of water level (as reference). Head in ASR well number 1 was rose up to 73 m in the third prior cycle which was 15 m above the reference. In the last cycle, the head was 14 m below the reference. The head in the other wells are shown in Table 12 with reference to the initial head.

Table 12 Maximum and Minumum value of Head for ASR wells (Run 1)

ASR well	The initial value (amsl)	Max. rise above ref.	Maximum decline below ref.
ASR well 2	58 m	+14 m	-12 m
ASR well 3	60 m	+14 m	-17 m
ASR well 4	58 m	+14 m	-14 m
ASR well 5	58 m	+14 m	-12 m
ASR well 6	60 m	+14 m	-16 m
ASR well 7	58 m	+15 m	-13 m
ASR well 8	59 m	+14 m	-14 m

After the end of the prior cycles (one year), the target storage volume (storage zone and buffer zone) has developed around the well. The results from MT3D show in Fig 43 that the buffer zone (light blue) is as barrier to the native groundwater (green), that has high TDS value, from the storage zone (dark blue) that has potable water.

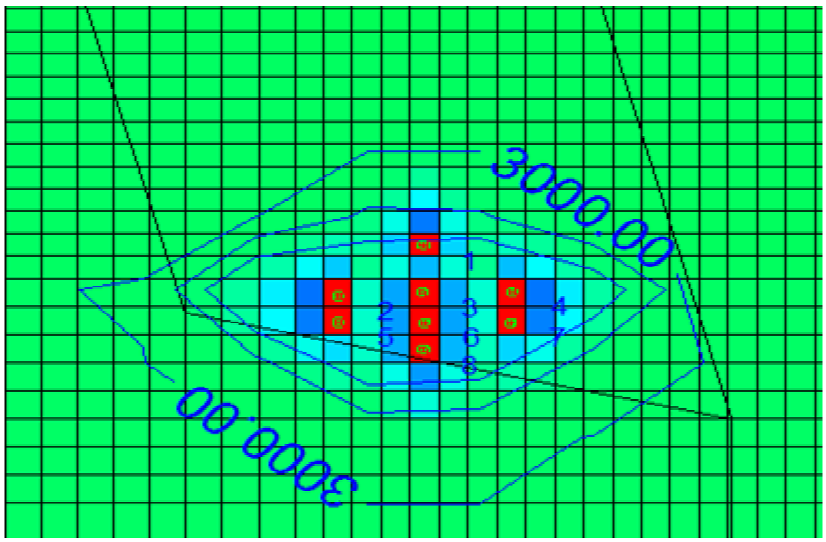


Figure 43 Top View for the Buffer zone storage zone after the end of first year (Run 1)

Groundwater Vistas can display the result from MT3D in cross-section along the row or column in the model, which helps to define the storage zone and buffer zone around the well. The diameter of the storage zone is almost 100 m after the prior cycles (one year) and the distance from the end of storage zone to buffer zone is 100 m.

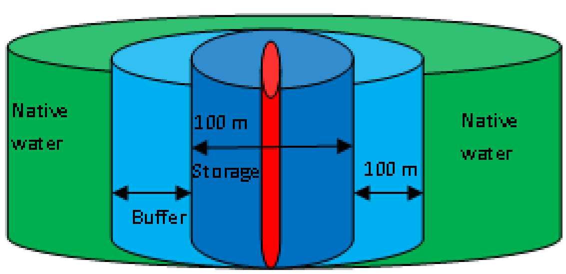


Figure 44 schematic for storage zone and buffer zone after the end of first year

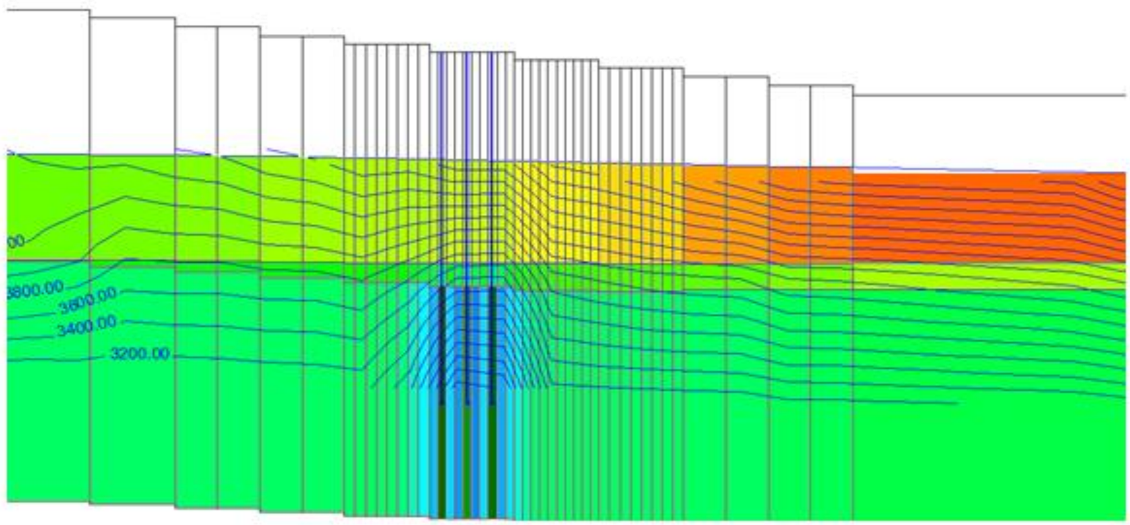


Figure 45 Cross-Section a long Row 38 after the end of first year (Run 1)

The hydrograph chart for ASR well number 1 showed the TDS concentration has been improved surround the well due to operation of the prior cycles. The concentration reached 500 mg/L at the beginning of the first basic cycle. Then, it fluctuated between 500 mg/L and 1000 mg/L, which is the concentration of the recovery volume and less than the allowable standard limit of potable water in Kuwait.

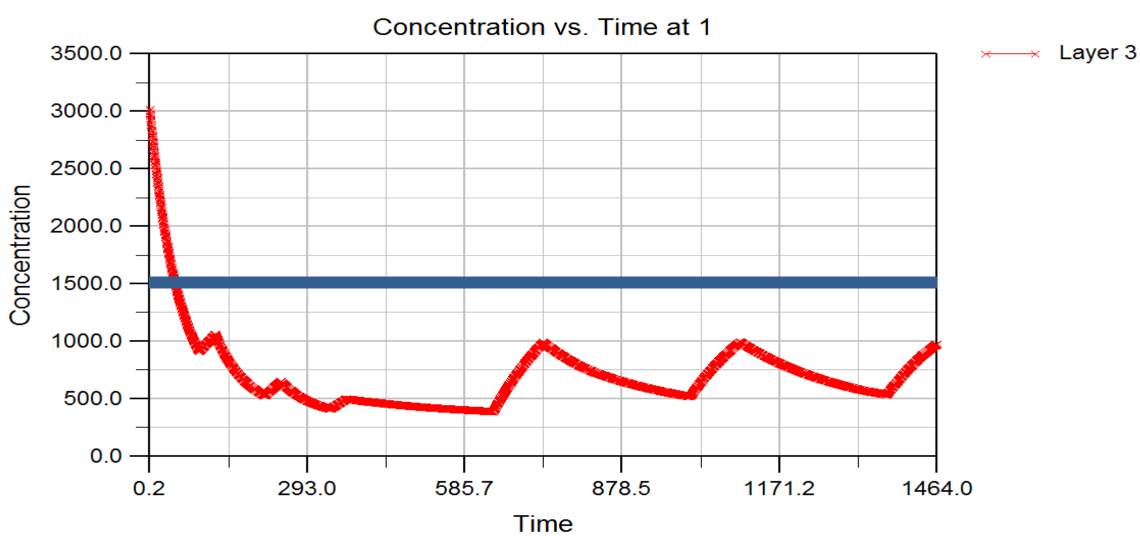


Figure 46 Hydrograph of TDS Concentration for ASR well 1 (Run 1)

The recovery efficiency percentage for ASR well number 1 per each basic cycle was calculated from the equation below.

$$Recovery\ efficiency\ = \frac{Volume\ of\ water\ recovered\ with\ TDS \leq 1500\,\frac{mg}{L}}{Volume\ of\ water\ injected}$$

$$= \frac{(1250\ m^3\ per\ day) * (93\ days)}{(550\ m^3\ per\ day) * (\ 273\ days)} * (100) =\ 77.42\ \%$$

The total daily recovery volume from 8 ASR wells with TDS less than 1500 mg/L is designed to provide 10000 m^3. All of the other ASR wells had the same recovery efficiency (77.42%) based on the hydrograph chart for each well. The recovery efficiency can be increased by increasing the total recovery, but one of the objectives of applying ASR was improvement in water quality in the aquifer by leaving a small percentage (22.57%) of the injected water in the aquifer. The injected and recovered water in prior cycles were a one time investment to create the transition zone and they were not considered in the calculation of the recovery efficiency percentage.

Table 13 TDS value at end of Prior Cycles and Basic Cycles for ASR wells (Run 1)

ASR well	Initial TDS value	TDS at end of prior cycles	TDS at end of basic cycles
ASR well 2	3000 mg/L	450 mg/L	800 mg/L
ASR well 3	3000 mg/L	510 mg/L	760 mg/L
ASR well 4	3000 mg/L	500 mg/L	800 mg/L
ASR well 5	3000 mg/L	600 mg/L	1200 mg/L
ASR well 6	3000 mg/L	400 mg/L	760 mg/L
ASR well 7	3000 mg/L	600 mg/L	1150 mg/L
ASR well 8	3000 mg/L	500 mg/L	1150 mg/L

4.4.2. Comparison between Run 2 and 3

Run 2 was applied in the fairly suitable site (grade 3) while Run 3 was in the best suitable site (grade 4). Both of these runs have the same distribution of wells and well spacing of 200 m from center to center.

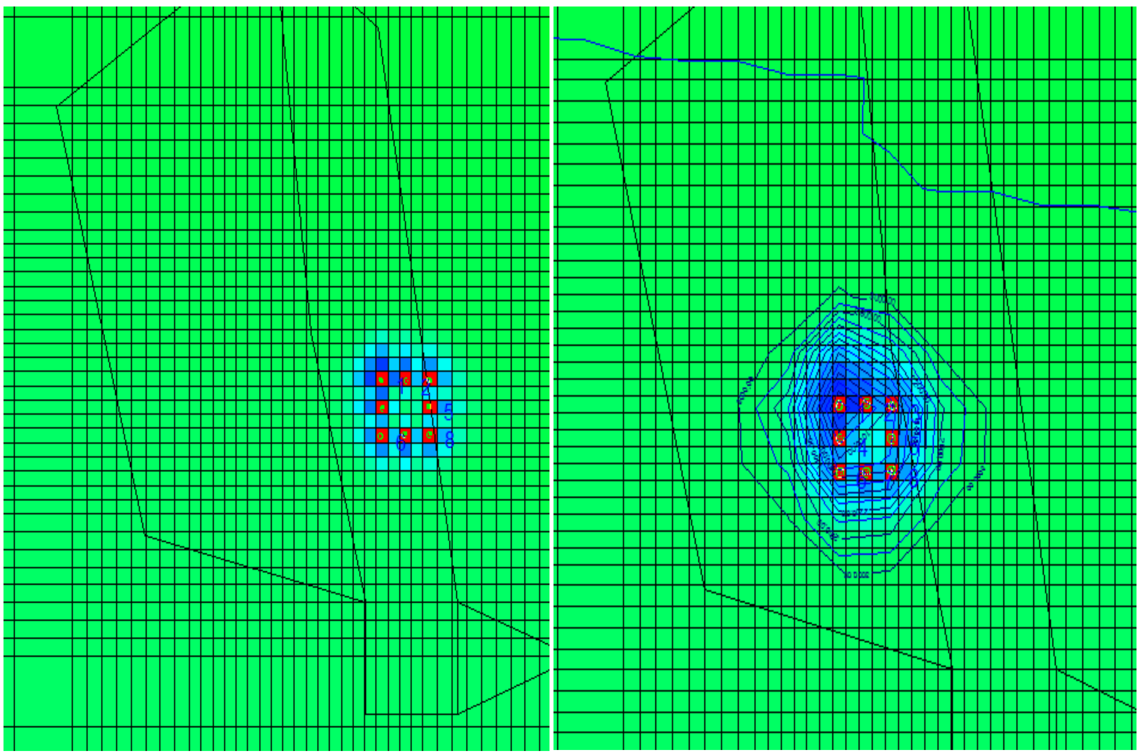


Figure 47 Top view for Run 2 (Left) and Run 3 (Right) after the end of first basic cycle

All of ASR wells in both runs provided the required volume of water with good water quality in the recovery phases. It was noticed from runs 2 and 3, ASR well number 1 provided water quality less than 250 mg/L during recovery phases. The arrangement of wells resulted in movement of injected water to the North-West of the ASR field for ASR well number 1. The water injected from all wells was moved immediately when the prior cycle was started to ASR well number 1. The diameter of the storage zone for ASR well

1 was 400 m and the distance from the storage zone to the end of the buffer zone was 200 m.

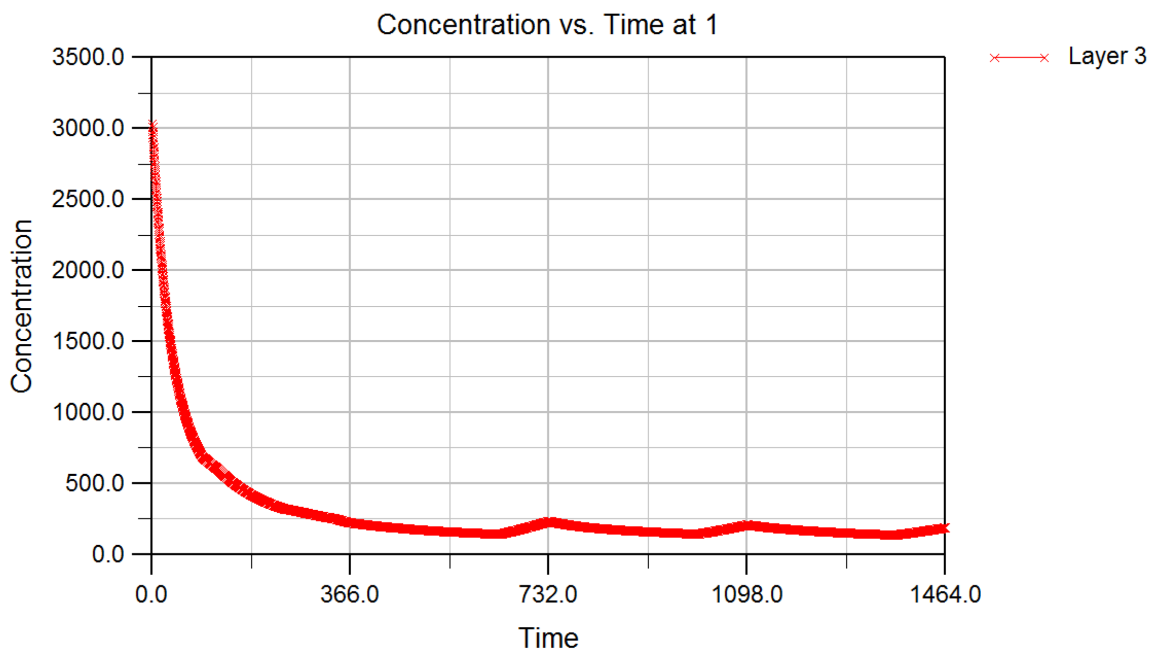


Figure 48 Hydrograph of TDS Concentration for ASR well 1 (Run 2)

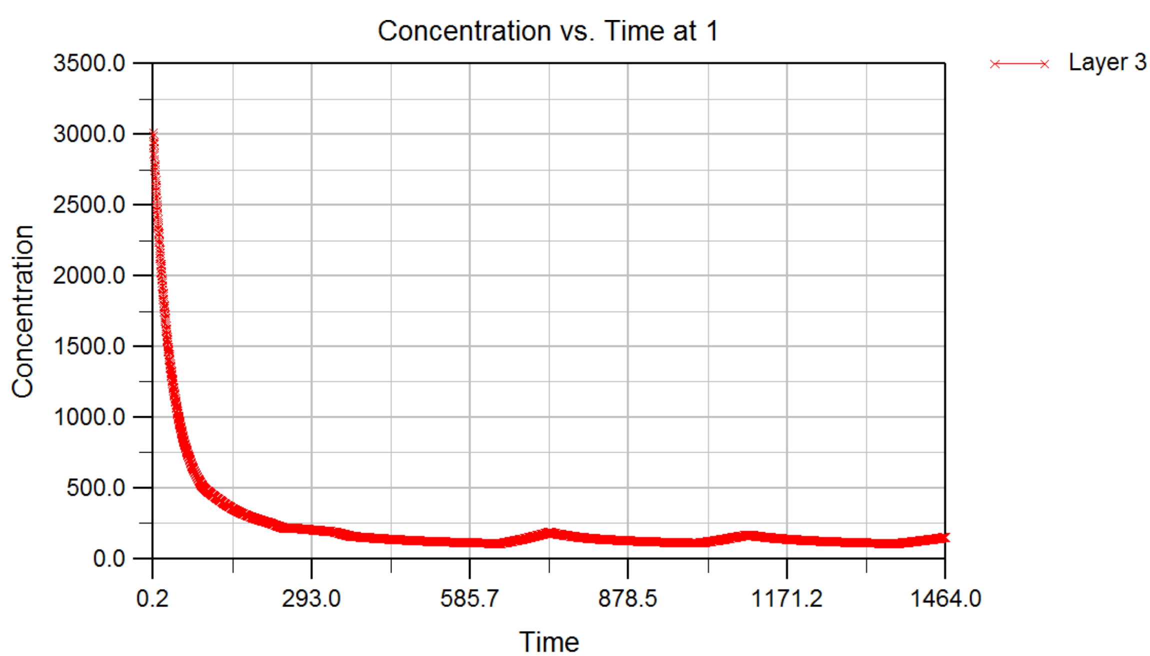


Figure 49 Hydrograph of TDS Concentration for ASR well 1 (Run 3)

4.4.3. Run 4:

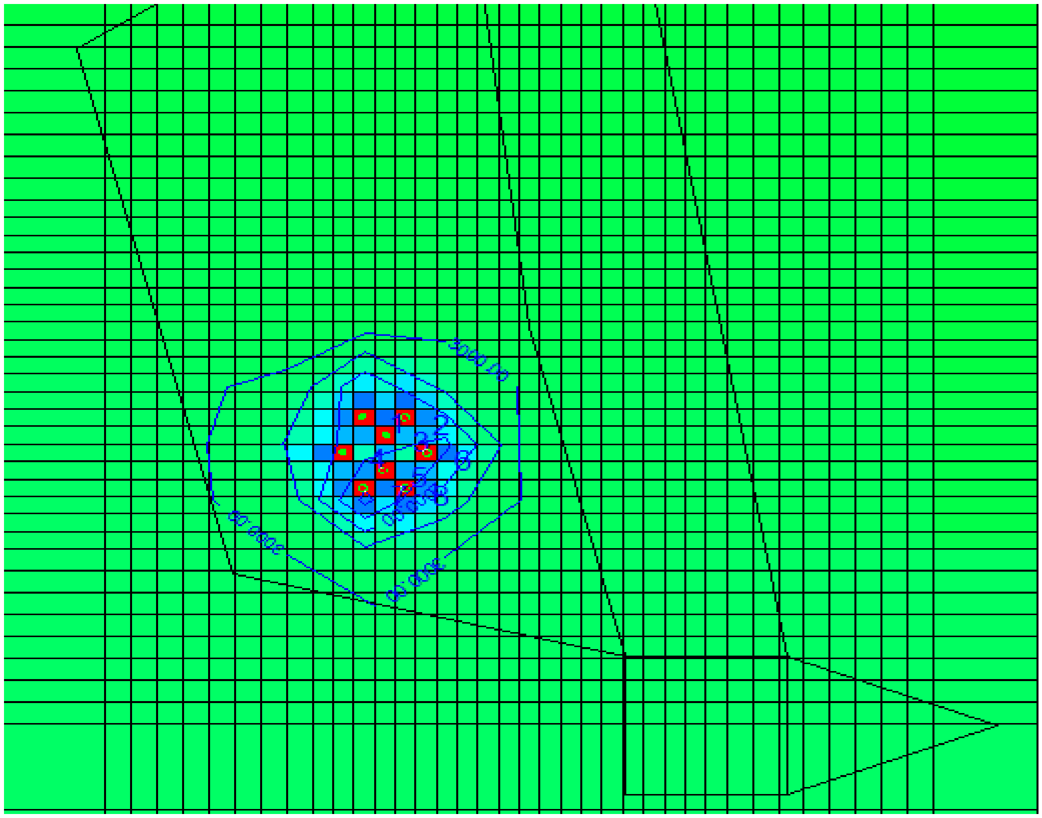


Figure 50 Top View for the buffer zone and storage zone around ASR wells after the end of first basic cycle (Run 4)

This run followed the first scenario which has prior cycles (one year) and ASR basic cycles (3 years). It has an excellent distribution for ASR wells with well spacing of 200 m and total surface area for the ASR field of 500 m x 500 m in the best suitable site for ASR. In this run, the recovery efficiency was 77.42 % and it meets the requirement of daily recovery volume of water and improves the water quality in ASR field. The head level during the ASR operation in this run was within the allowable limits for rising and declining the water head level (+20 m or -20 m with reference to initial water head level). For each ASR well, the storage zone has a diameter 300 m and the distance between the radius of buffer zone and the storage zone was 200 m.

4.4.4. Run 5:

The ASR wells in this run were unorganized and have different spacing between wells. All of them were in the best suitable site except ASR well number 1, which was in the least suitable site, and ASR well number 8, which was in the fairly suitable site. The storage zone with TDS less than 1500 mg/L was created with a very small diameter, just enough to meet the recovery volume in recovery phases. The total recovery percentage was 77.42 %.

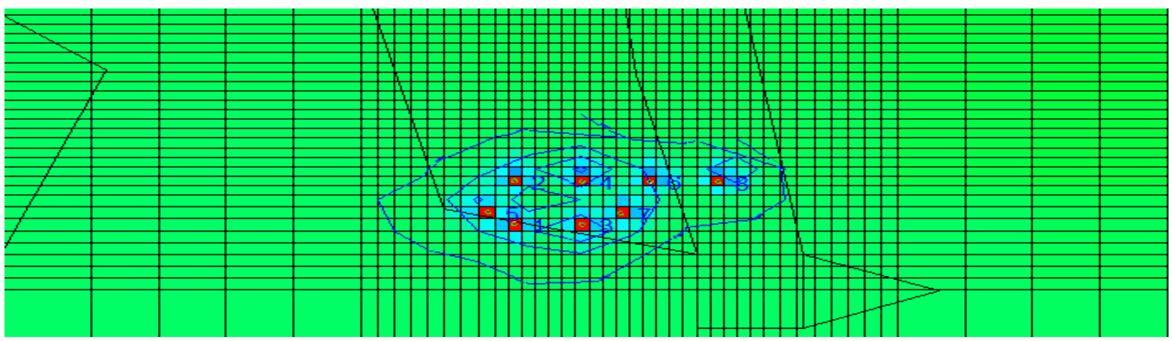


Figure 51 Top View for ASR field after end of first year (Run 5)

Table 14 TDS value at end of Prior Cycles and Basic Cycles for ASR wells (Run 5)

ASR well (Run5)	Initial TDS value	TDS value at end of prior cycles	TDS value at end of basic cycles
ASR well 1	3000 mg/L	650 mg/L	1200 mg/L
ASR well 2	3000 mg/L	500 mg/L	1200 mg/L
ASR well 3	3000 mg/L	500 mg/L	1220 mg/L
ASR well 4	3000 mg/L	500 mg/L	1220 mg/L
ASR well 5	3000 mg/L	750 mg/L	1250 mg/L
ASR well 6	3000 mg/L	500 mg/L	1200 mg/L
ASR well 7	3000 mg/L	750 mg/L	1250 mg/L
ASR well 8	3000 mg/L	700 mg/L	1200 mg/L

4.4.5. Run 6

The distribution of ASR wells in this run was oriented perpendicular to that of run 5 and the well spacing was between 200 m and 212.5 m. The total recovery volume from 8 ASR wells was 93000 m^3 for 93 days and the total injection volume of water in the first ASR basic cycle was 1201200 m^3 for 273 days. The buffer zone only existed in the injection phases and then disappeared in the recovery phases, probability causing mixing between the native groundwater and storage zone.

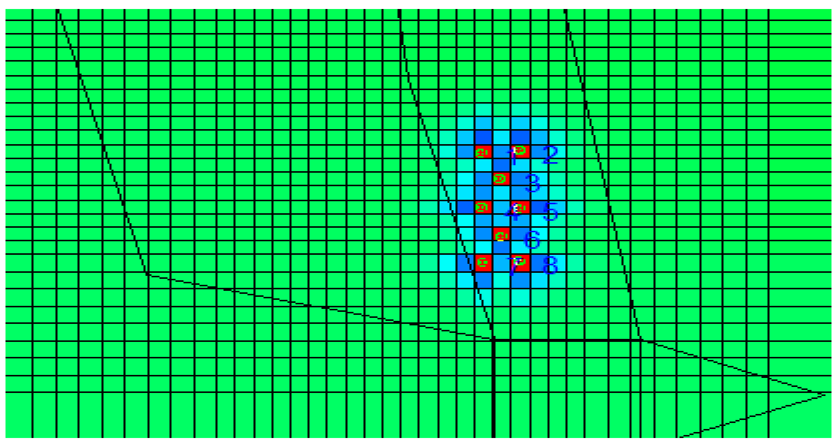


Figure 52 Top View for Run 6 after the end of Prior Cycles

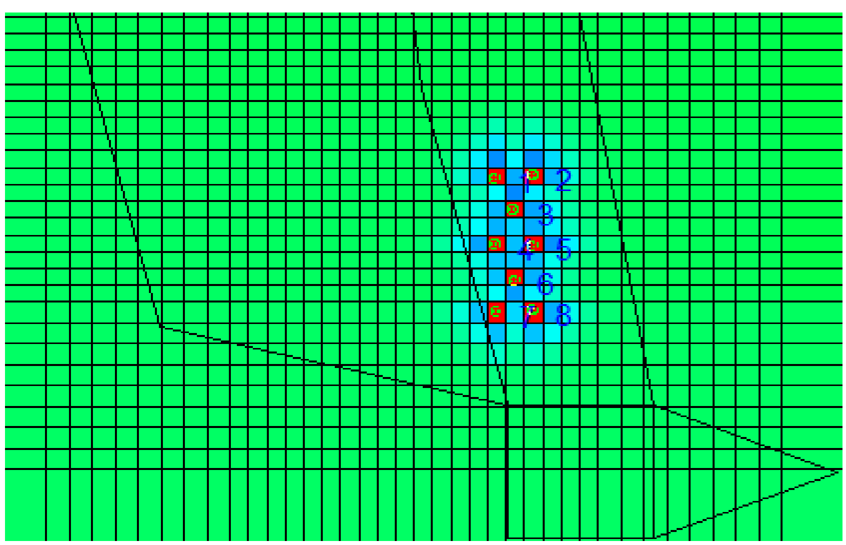


Figure 53 Top View for Run 6 after the end of First Basic Cycle

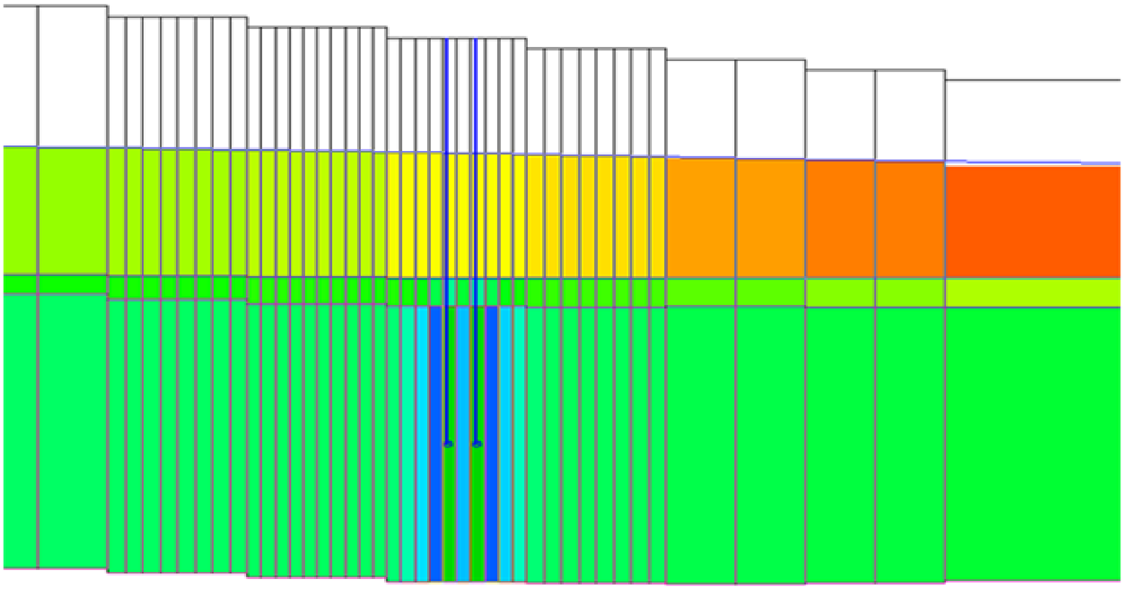


Figure 54 Cross-Section a long Row 30 after the end of Prior Cycles (Run 6)

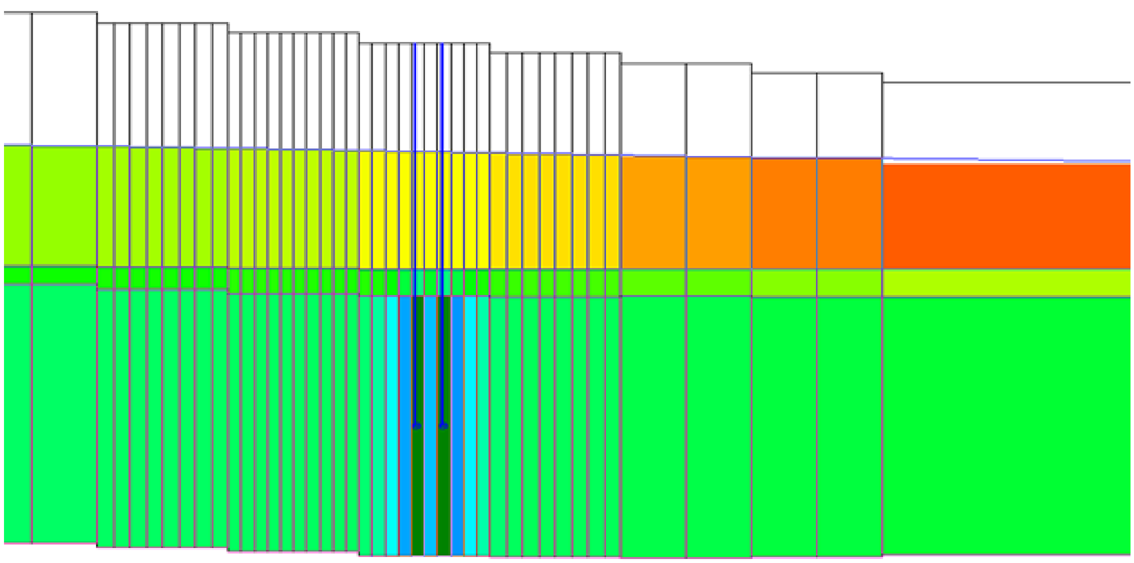


Figure 55 Cross-Section a long Row 30 after the end of First Basic Cycle (Run 6)

4.4.6. Comparison between Runs 7 and 8

In run 7, the total area occupied by ASR wells is 400 m x 200 m and this is a small land area when compared to the surface storage in Kuwait - five times the ASR field in this run. On the other hand, the ASR wells area in run 8 was 700 m x 300 m with well spacing of 200 m. The storage zone was located surround all of the ASR wells and the buffer zone is protection for the storage zone from mixing with native zone.

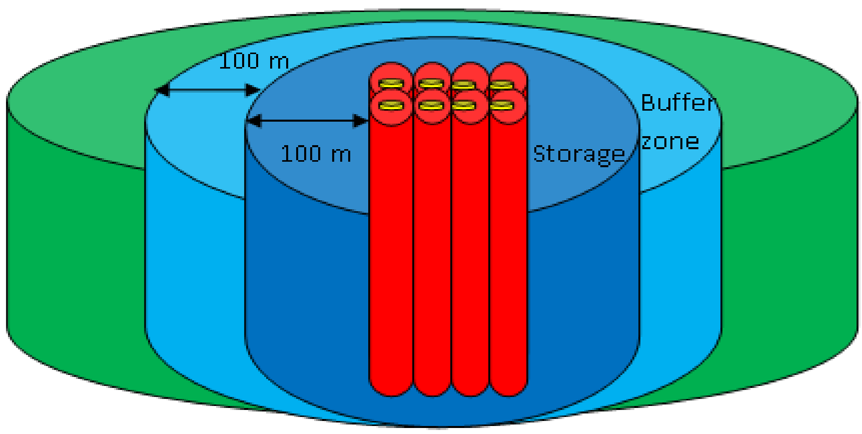


Figure 56 Schematic for Storage Zone and Buffer Zone in Run 7

Another advantage from using the distribution used in run 7 is that the storage zone is represented mathematically in the equation below.

Storage Zone (TDS less than 1500 mg/L) = wells zones + the zone surround wells

In run 8, each ASR well has own storage zone while they share the buffer zone. The recovery volume of water from the wells in the middle has almost the same TDS value (between 250 mg/L and 500 mg/L) and the TDS of the recovery volume from the wells at the edge is between 400 mg/L and 750 mg/L. The total recovery efficiency for runs 7 and

8 was expected to meet the desirable percentage due to being located on the best suitable site and using uniformed well spacing between them.

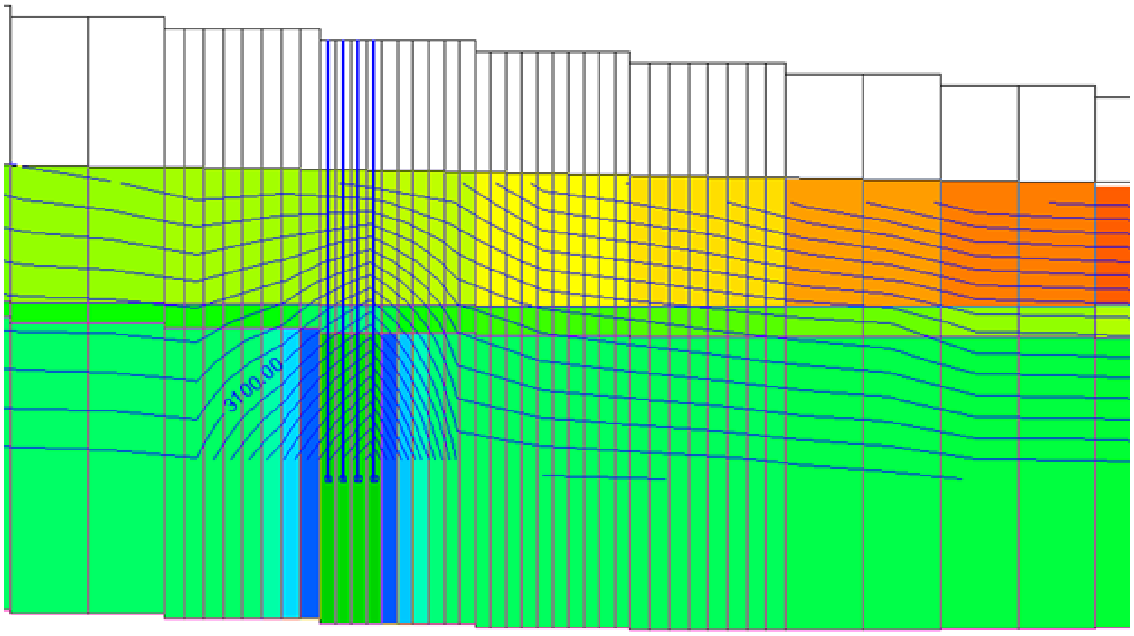


Figure 57 Cross-Section a long Row 32 after the end of first year in Run 7

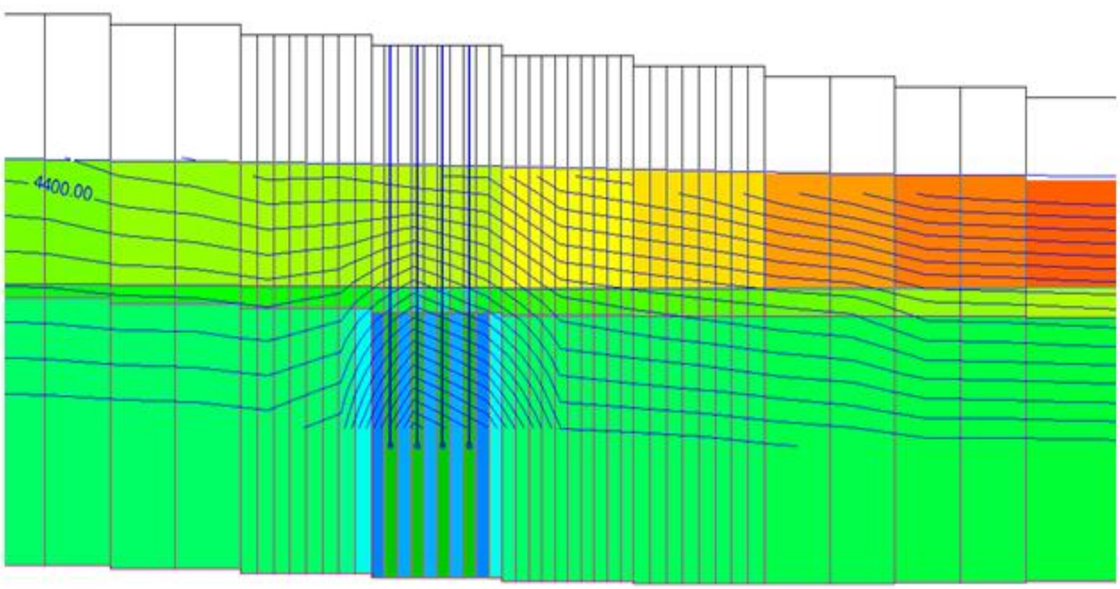


Figure 58 Cross-Section a long Row 32 after the end of first year in Run 8

4.4.7. Second Scenario (Runs 9 and 10)

The second scenario was applied on runs 9 and 10 consisting of continuous injection during the project and three basic ASR cycles starting after the first year. Two wells were implemented in the injection phase with constant daily injection rates (550 m^3 per well) and 8 recovery wells were located in the best suitable area for ASR and worked in basic ASR cycles: 550 m^3/day per well in the injection phase and 1250 m^3/day per well in the recovery basic phase. In run 9 after one year of injecting water, the water quality improved in all wells except well numbers 5 and 7 which had no change in TDS value (3000 mg/L). The injected water which moved from the injection wells to the East of the ASR field reached 1750 mg/L TDS in that area after one year. The recovery volume for well number 5 did not meet the requirement of TDS less than 1500 mg/L except in the first recovery phase.

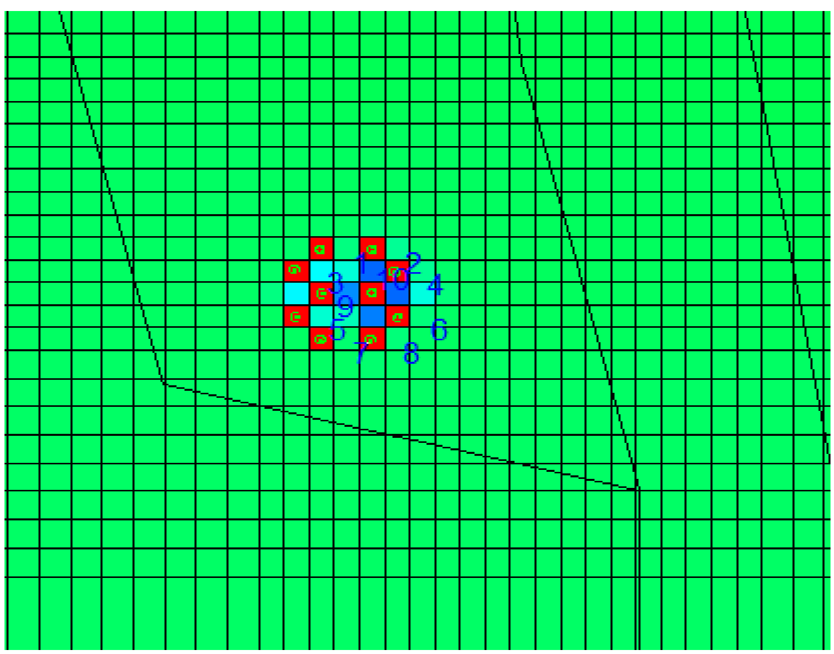


Figure 59 Top View for Run 9 after the end of first Basic Cycle

The storage zone for wells 3 and 4 were connected to be as one zone after the first basic ASR cycle which created a large zone in the middle with good water quality. The diameter of the storage zone is 400 m which is limited between ASR wells 4 and 3 and the buffer zone surrounding the storage zone is 100 m.

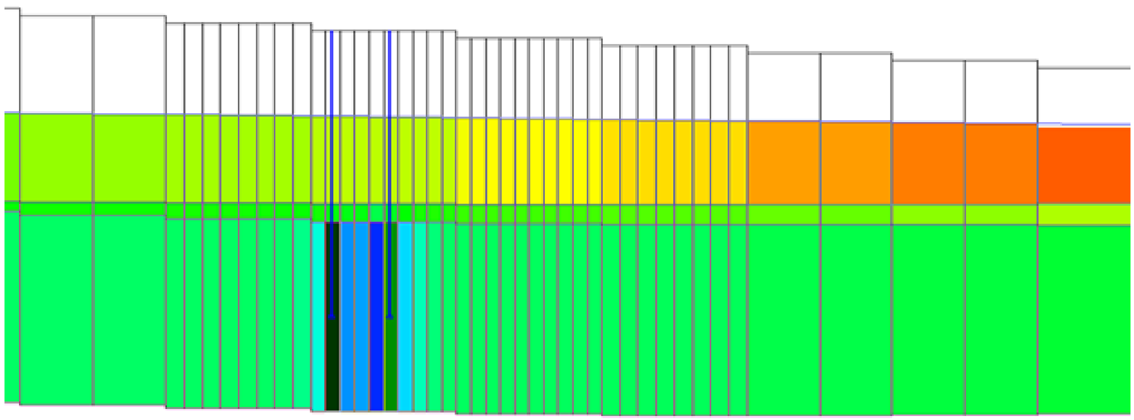


Figure 60 Cross-Section along row 30 For Run 9 After the end of first Basic Cycle

At the end of last basic cycles, the storage zone is located in a large circle that has potable water with a total area of 196350 m^2 and the buffer zone surrounding it with 200 m.

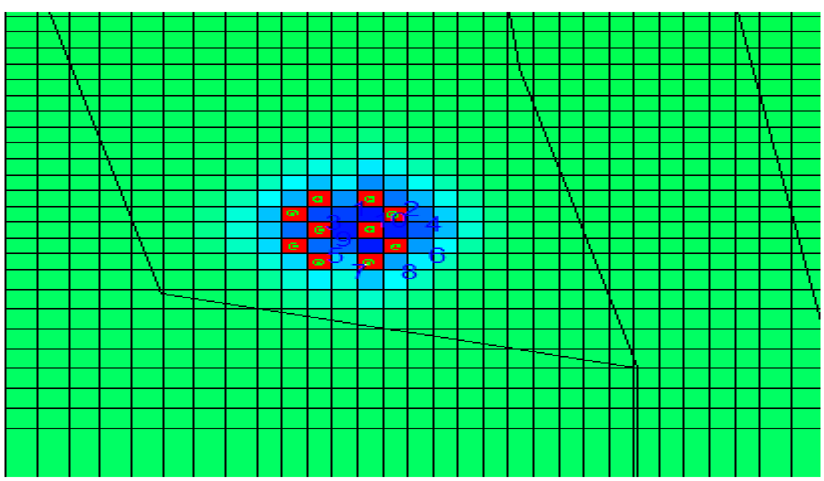


Figure 61 Top View for Run 10 after the end of First Basic Cycle

Table 15 TDS concentration and the Volume of water recovered during Run 9

ASR well	Initial TDS mg/L	TDS at the end prior cycles mg/L	TDS at the end first basic ASR cycle	TDS at the end second basic ASR cycle	TDS at the end third basic ASR cycle	The volume of water recovered from the three basic ASR cycles (m^3)			The total recovery efficiency percentage from the three basic ASR cycles		
well 1	3000	27500	1500 mg/L	1150 mg/L	850 mg/L	116250	116250	116250	77.42 %	77.42 %	77.42 %
well 2	3000	2000	1100 mg/L	750 mg/L	600 mg/L	116250	116250	116250	77.42 %	77.42 %	77.42 %
well 3	3000	2750	1500 mg/L	1200 mg/L	900 mg/L	116250	116250	116250	77.42 %	77.42 %	77.42 %
well 4	3000	1750	750 mg/L	500 mg/L	400 mg/L	116250	116250	116250	77.42 %	77.42 %	77.42 %
well 5	3000	2850	1750 mg/L	1300 mg/L	1100 mg/L	77500	116250	116250	51.61 %	77.42 %	77.42 %
well 6	3000	2220	1150 mg/L	800 mg/L	650 mg/L	116250	116250	116250	77.42 %	77.42 %	77.42 %
well 7	3000	2980	1850 mg/L	1500 mg/L	1250 mg/L	96875	116250	116250	64.51 %	77.42 %	77.42 %
well 8	3000	2400	1500 mg/L	1200 mg/L	1000 mg/L	116250	116250	116250	77.42 %	77.42 %	77.42 %

In run 10, the injected water moved from the injection wells to the south of the ASR field which improved the water quality in the first year in that area from 3000 mg/L to 2000 mg/L. The distribution of wells in ASR field plays an important role in the recovery volume of water and improvement the groundwater due to the change in location of the injection wells in the middle of field. ASR wells number 3 and 4 provided water with TDS of 1500 mg/L in the first two month (ASR well 3) and 77 days (ASR well 4) of the first basic recovery phase after which the recovery water exceeded the standard of potable water in Kuwait. The recovery efficiency for ASR wells 3 and 4 in the first ASR basic cycle were 51.61% and 64.51, respectively. The other ASR wells provided 1250 m^3/day per well and each met the desirable recovery efficiency (77.42 %). The area between ASR wells at the end of the project (storage zone) had a diameter of 500 m and the distance of buffer zone to the native groundwater was 200 m.

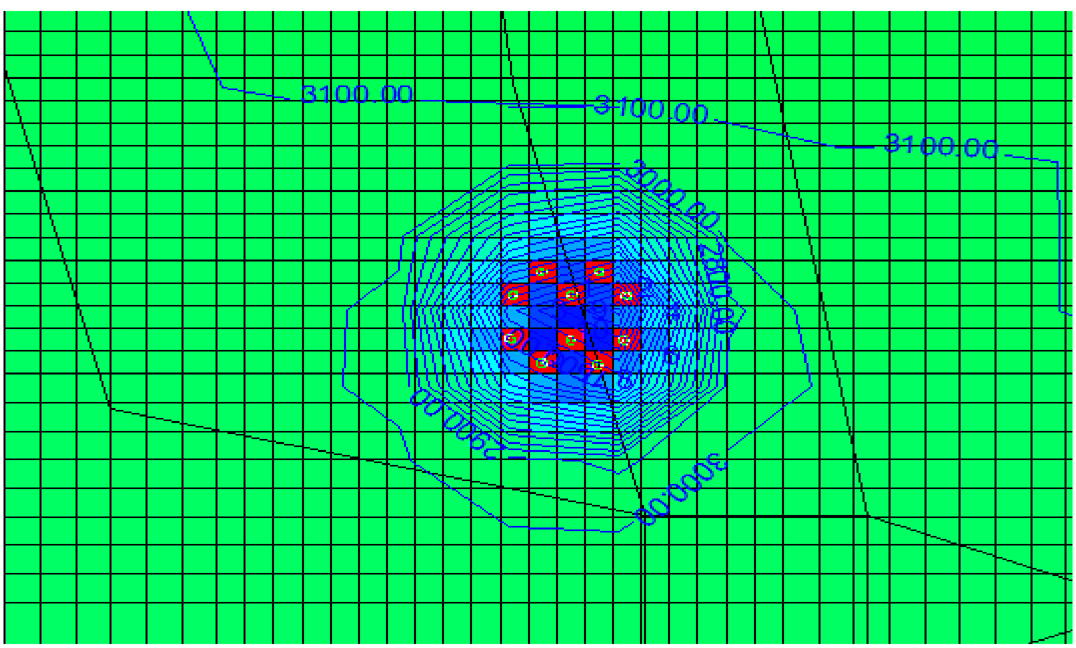


Figure 62 Top View for Run 10 after the end of first basic cycle

CHAPTER 5: Conclusion

Due to the growth of the population and increase in the standard living in Kuwait, the demand for freshwater has become extremely high in last two decades. Kuwait depends completely on desalination plants to provide freshwater. Sustainable water management is one of the solutions to reduce the pressure on the desalination plants in Kuwait. Aquifer Storage and Recovery (ASR) is a powerful technique for managing water resources for aquifers that have non-potable water or poor quality water and can be used for seasonal storage and a secondary water resource in time of need. The unused treated wastewater effluent (70% of the total production) from the Sulibiya wastewater plant (one of the biggest wastewater plants in the world) was investigated for injection in a suitable ASR site during the injection phase to create a potable water reserve. Numerical modeling was used to predict and analyze the best scenario for ASR in Kuwait that provides the best water quality in the recovery phase and improves the native groundwater. The produced water from ASR wells in the recovery phase is considered as groundwater and ASR removes the stigma of treated wastewater by injecting the water in the ground and then recoveries it later.

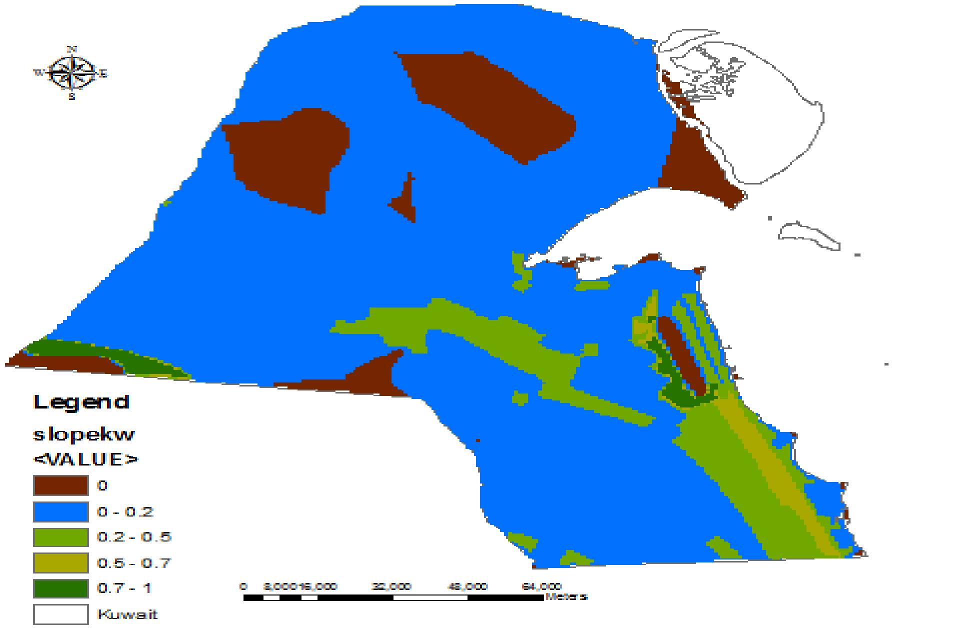
ArcGIS was used to collect all the production data from each desalination and wastewater treatment plant and the demand for freshwater in one database. In addition; the geodatabase is used to analyze and display the hydraulic parameters of groundwater of Kuwait, such as transmissivity, water level, top elevation of each aquifer, total dissolved solids, and hydraulic gradient. The four basic parameters needed to implement ASR operation are (1) software such as ArcGIS as a database for all of the water resource data of in Kuwait, (2) selection of a suitable site for ASR operation using GIS tools, (3) design the volume required in recovery phases and the duration of each cycle in injection and recovery phases, and (4) numerical modeling of the ASR operation.

Ten ASR scenarios were simulated in Groundwater Vistas software (using the MODFLOW and MT3D groundwater models) for the selected ASR operation site (Kabd area). There were two scenarios for the ASR operation; the first scenario used prior ASR cycles in the first year and basic ASR cycles for 3 years after that. The prior ASR cycles use 3 months of injection then one month of recovery implemented in one year to create a buffer zone between the injected water and native groundwater. The basic ASR cycle has 9 months injection followed by 3 months of recovery The basic ASR cycles are used in this project to determine the recovery efficiency each year. The first 8 runs followed the first scenario with different distributions and spacing of ASR wells to determine the optimum operation, while the last two runs followed a second scenario. The total daily recovery was 100000 m^3 from 8 ASR wells with 77.42 % of recovery efficiency. The second scenario continues the injection phase through two wells in the middle of the ASR field and basic ASR cycles with 8 ASR wells. The continuous injection phase injects 550 m^3/day per well during the ASR operation (4 years). The basic ASR cycle was started one year after the beginning of the ASR operation and used 9 months injection and 3 months recovery. In the second scenario, the TDS requirement was not met in the first recovery phase in some ASR wells.

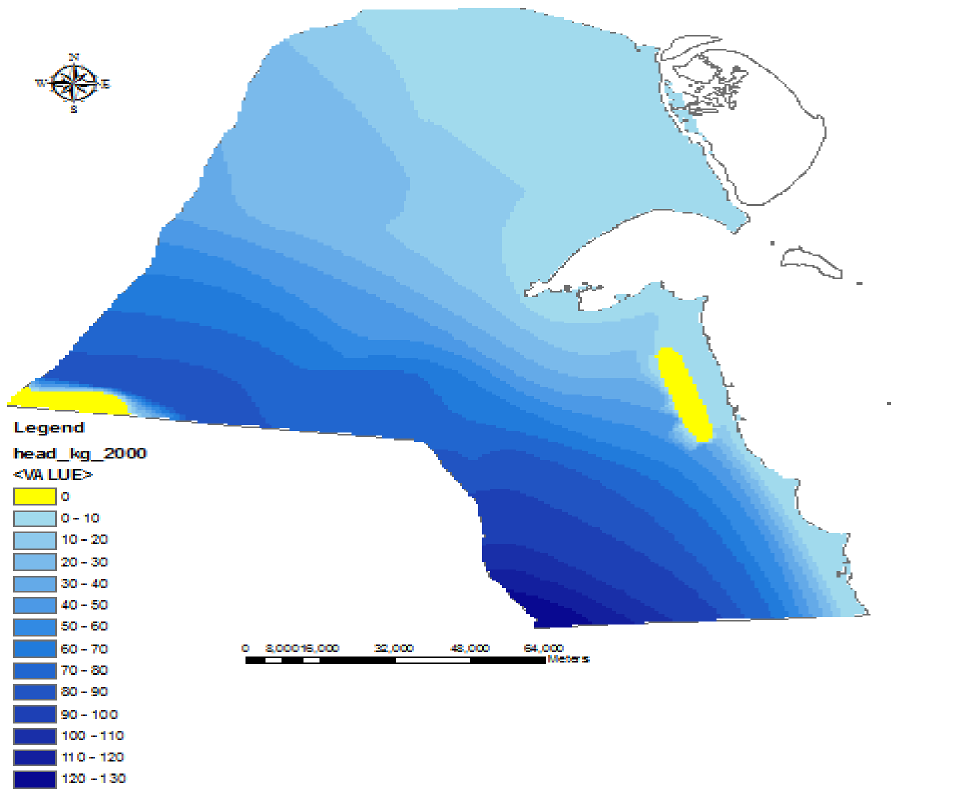
Future research should consider a more accurate definition of the depth of the portable storage zone and the buffer zone through additional numerical modeling. The distributions of all 10 runs are the best scenarios in the selected suitable site in Kuwait but they still need facilities and staff close to the ASR field for the monitoring and analysis of the ASR operation.

APPENDIX A: HYDRAULIC PROPERTIES IN ARCGIS

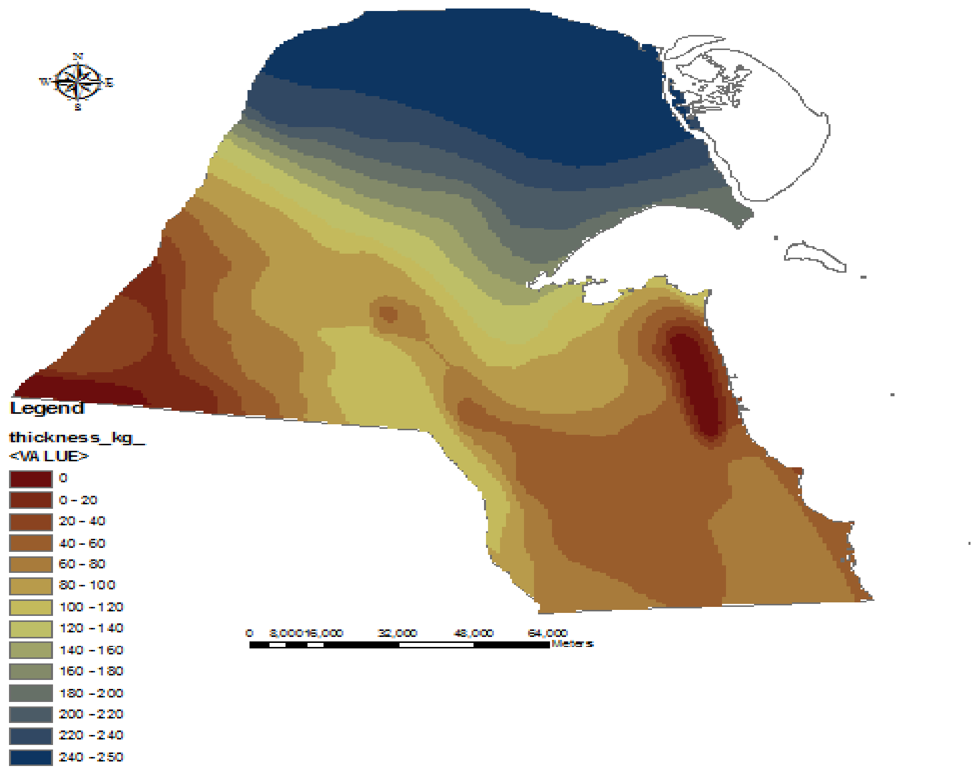
HYDRAULIC PROPERTIES OF KUWAIT AQUIFER GROUP



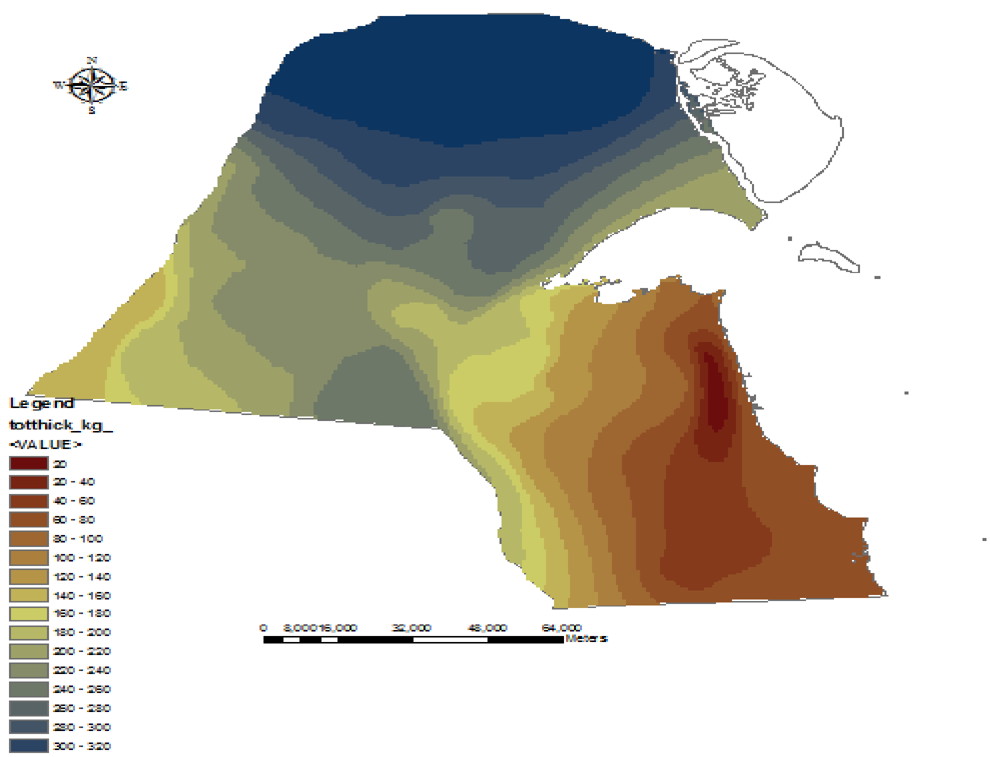
63 **Hydrulic Gradient (kuwait Group)**



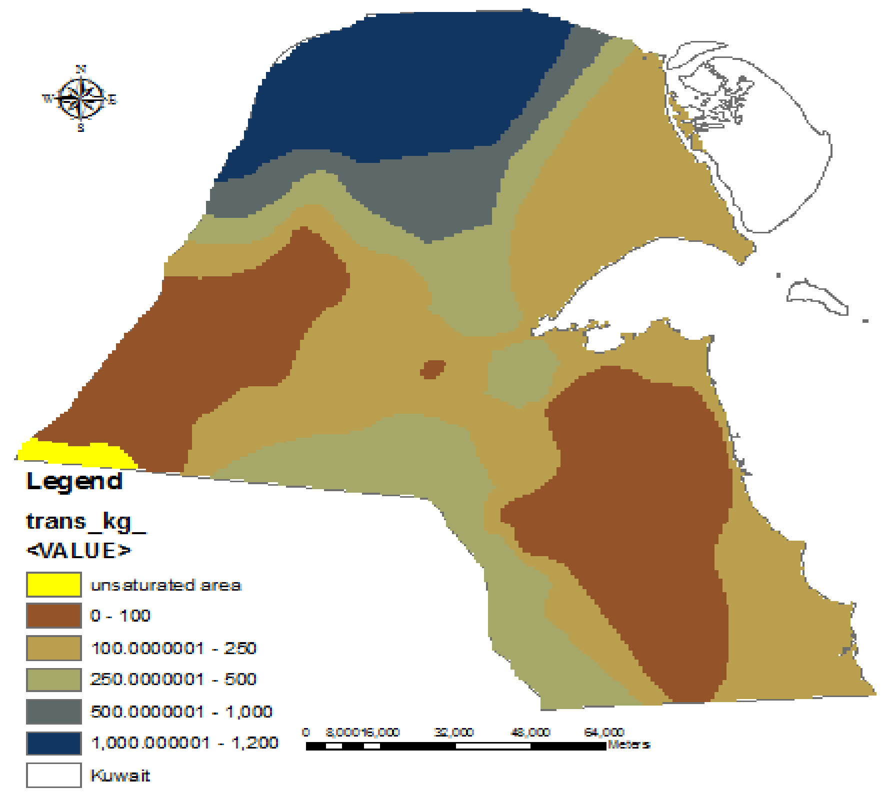
64 Water Level (Kuwait Group)



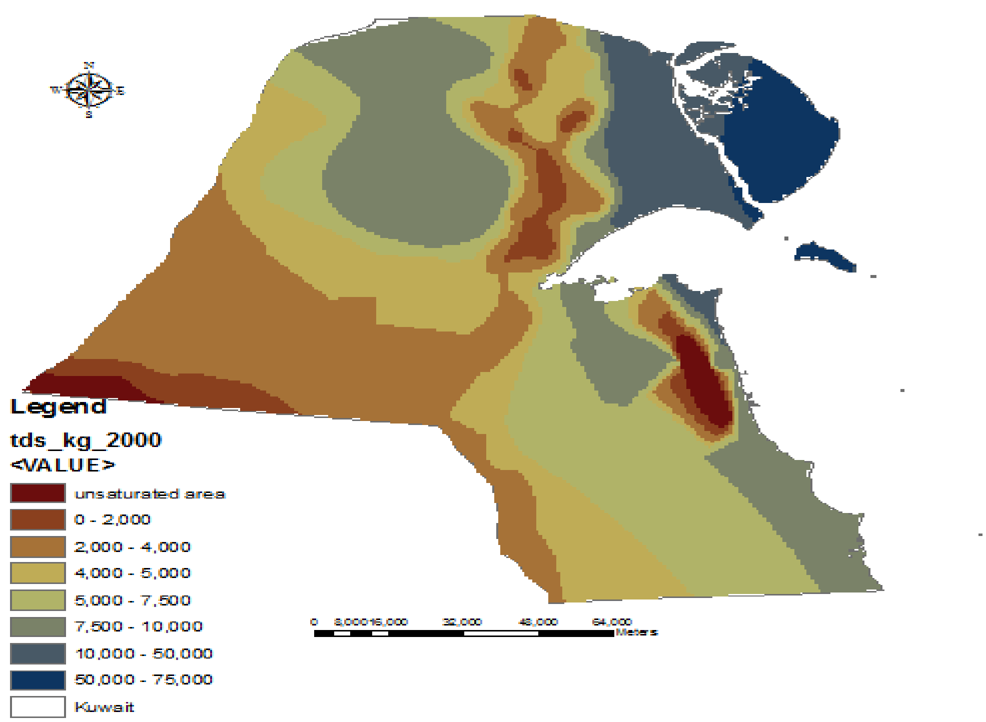
65 Saturated Thickness (Kuwait Group)



66 Total Thickness (Kuwait Group)

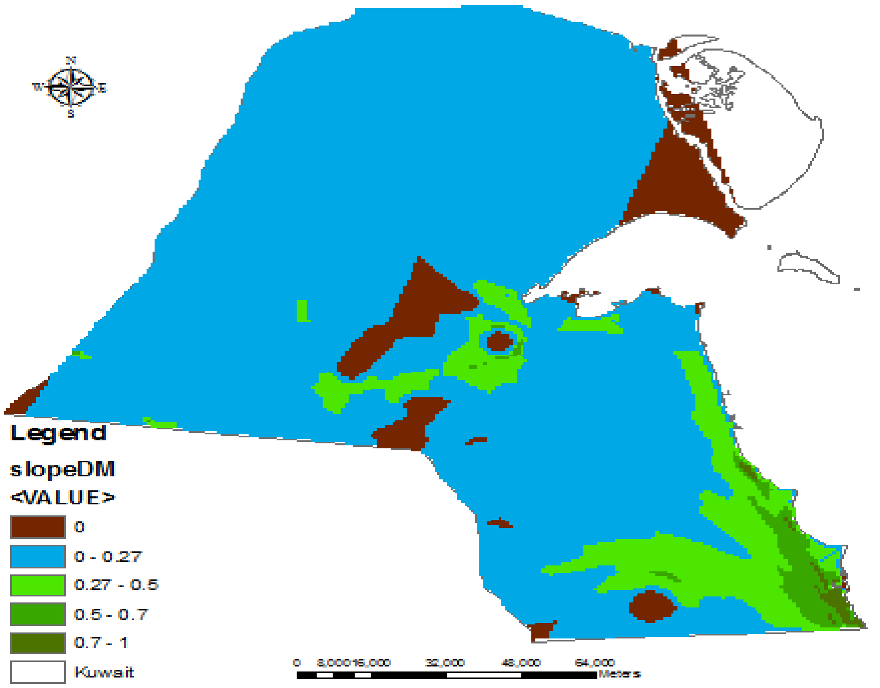


67 Transmissivity (Kuwait Group)

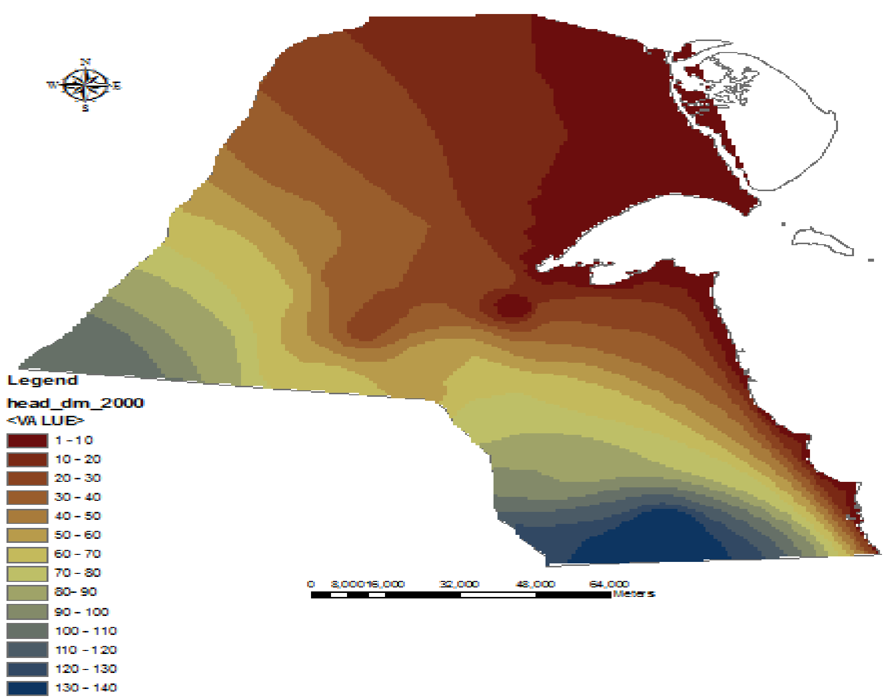


68 TDS (Kuwait Group)

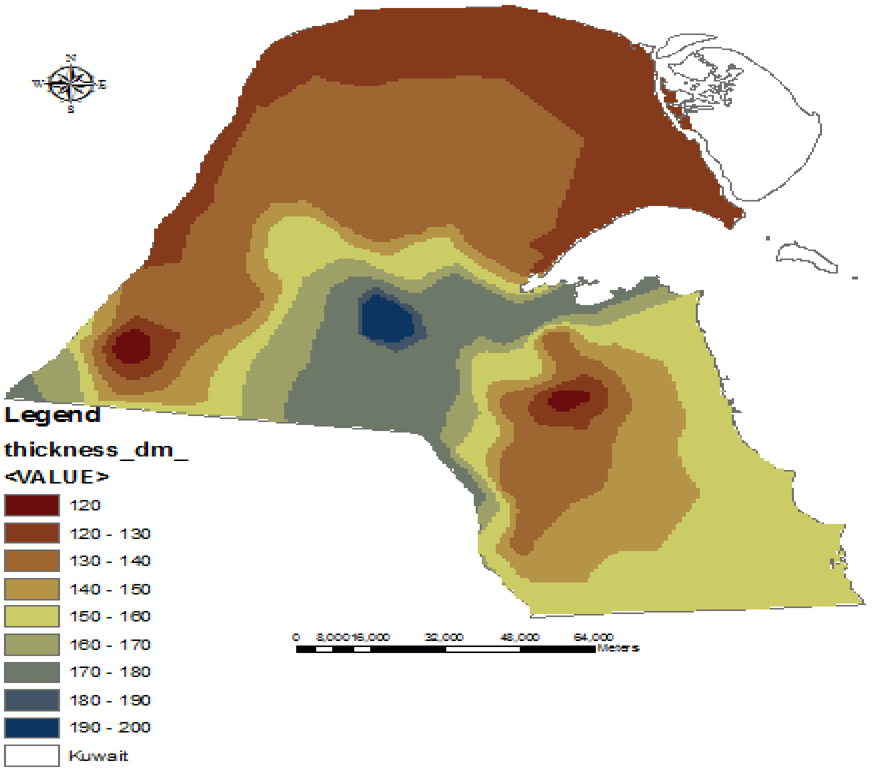
HYDRAULIC PROPERTIES OF DAMMAM AQUIFER



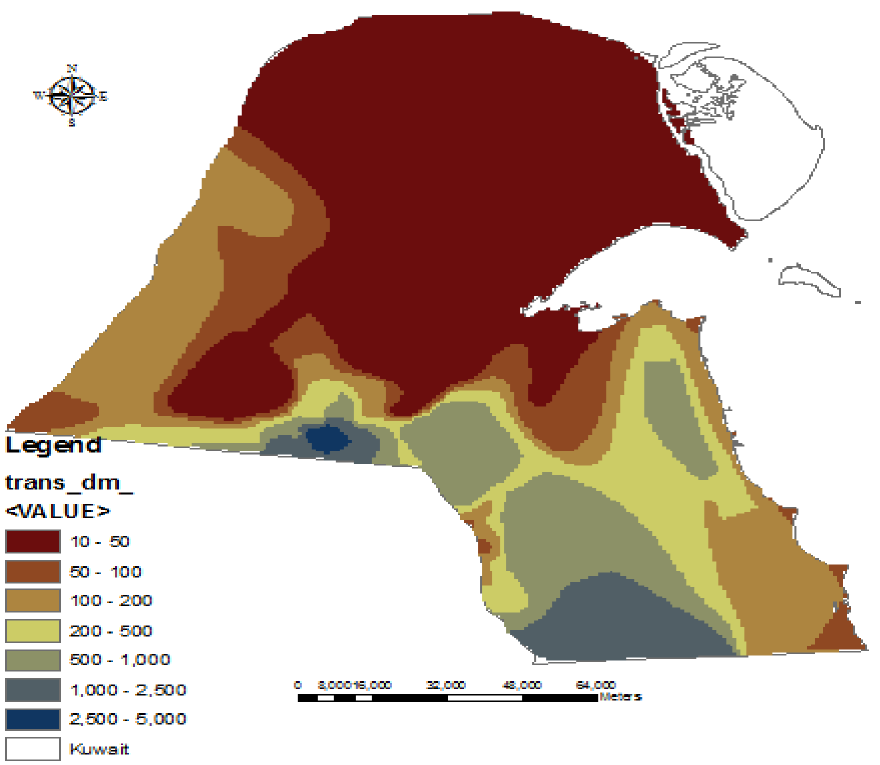
69 **Hydraulic Gradient (Dammam Aquifer)**



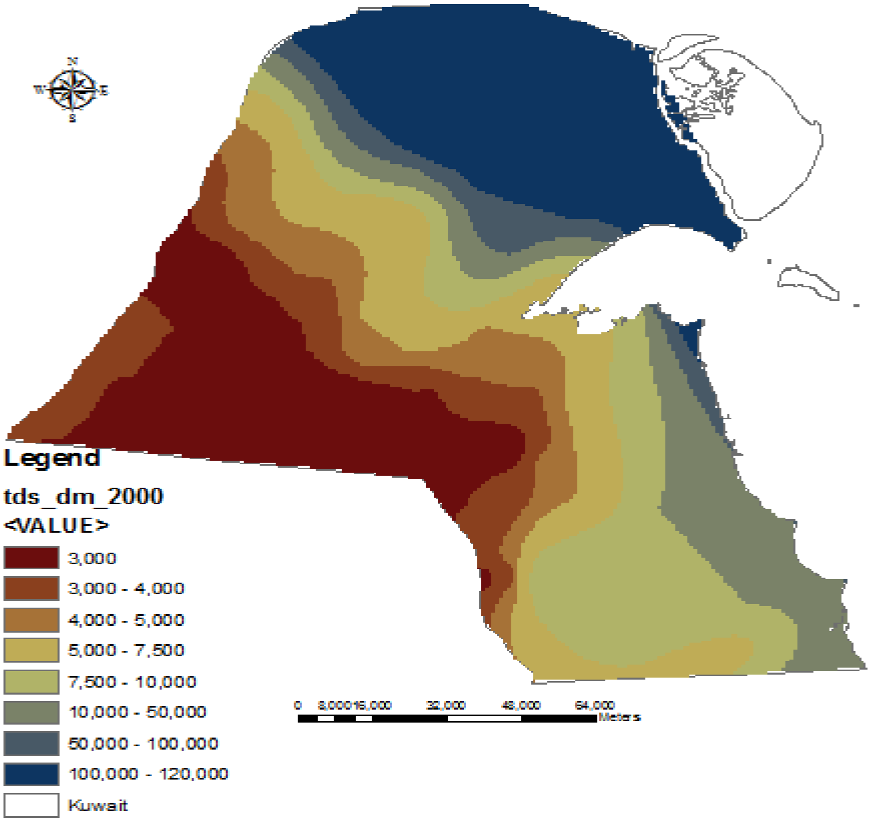
70 Potentiometric Head (Dammam Aquifer)



71 Thickness (Dammam Aquifer)



72 Transmissivity (Dammam Aquifer)

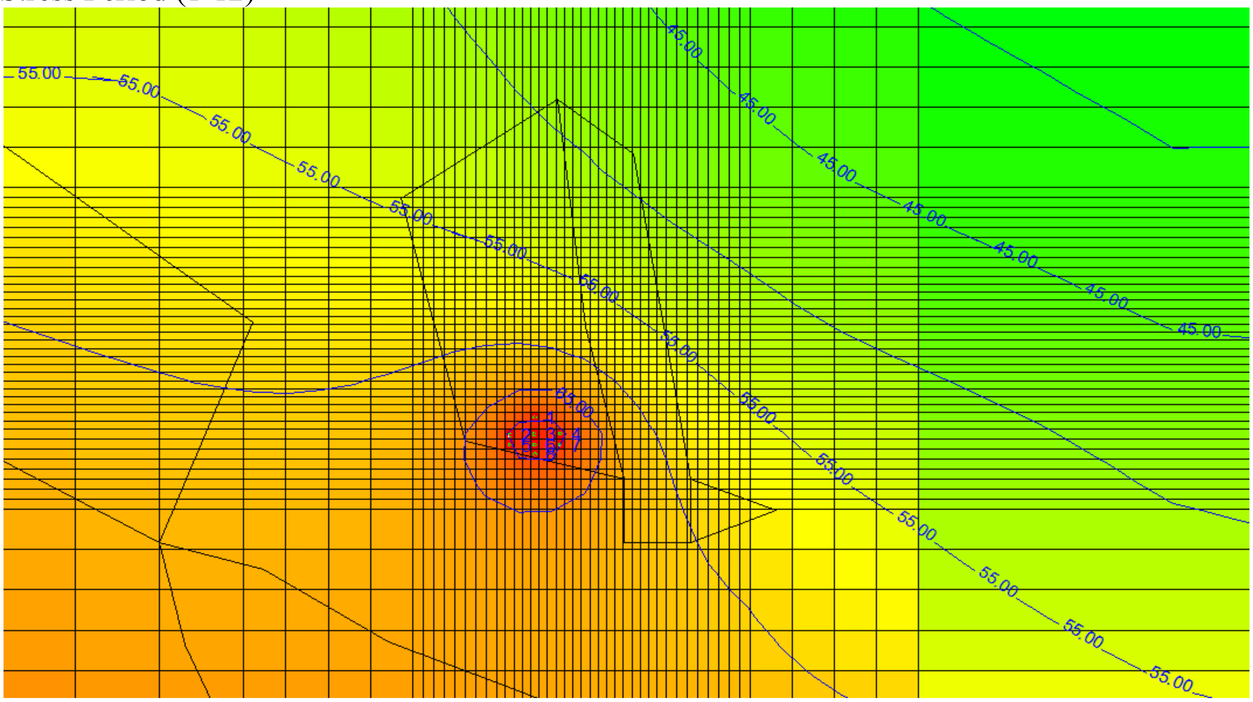


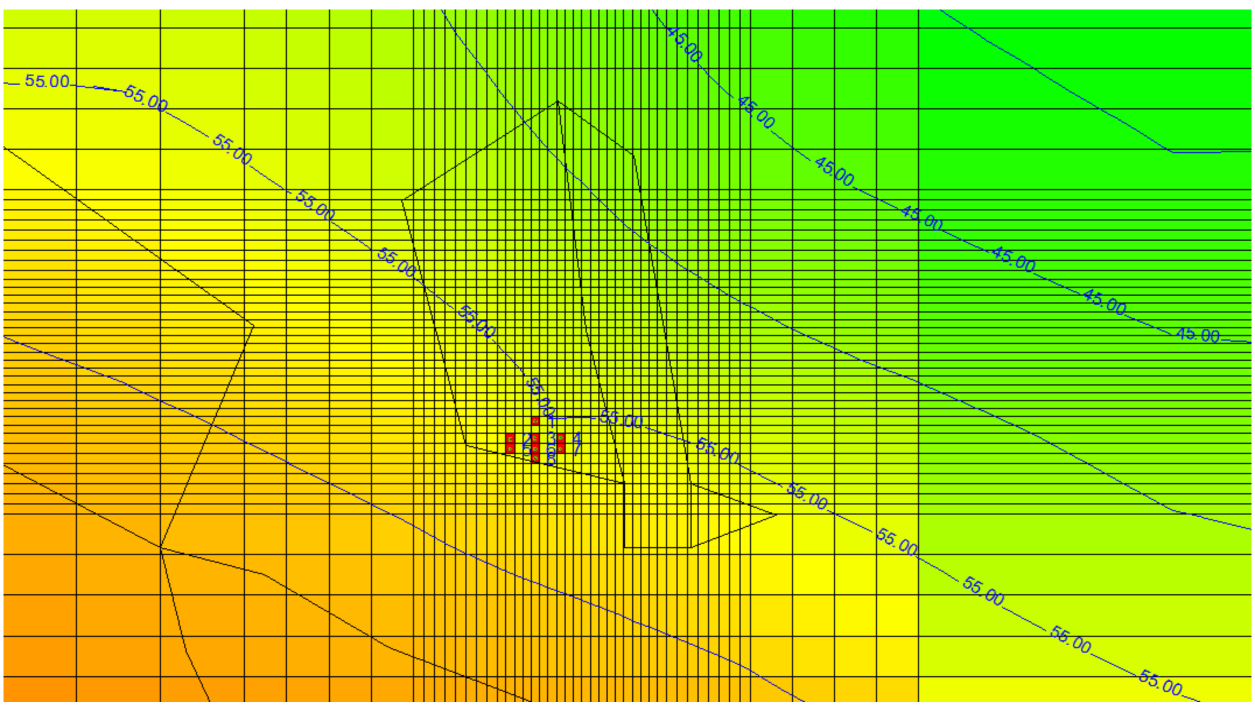
73 TDS (Dammam Aquifer)

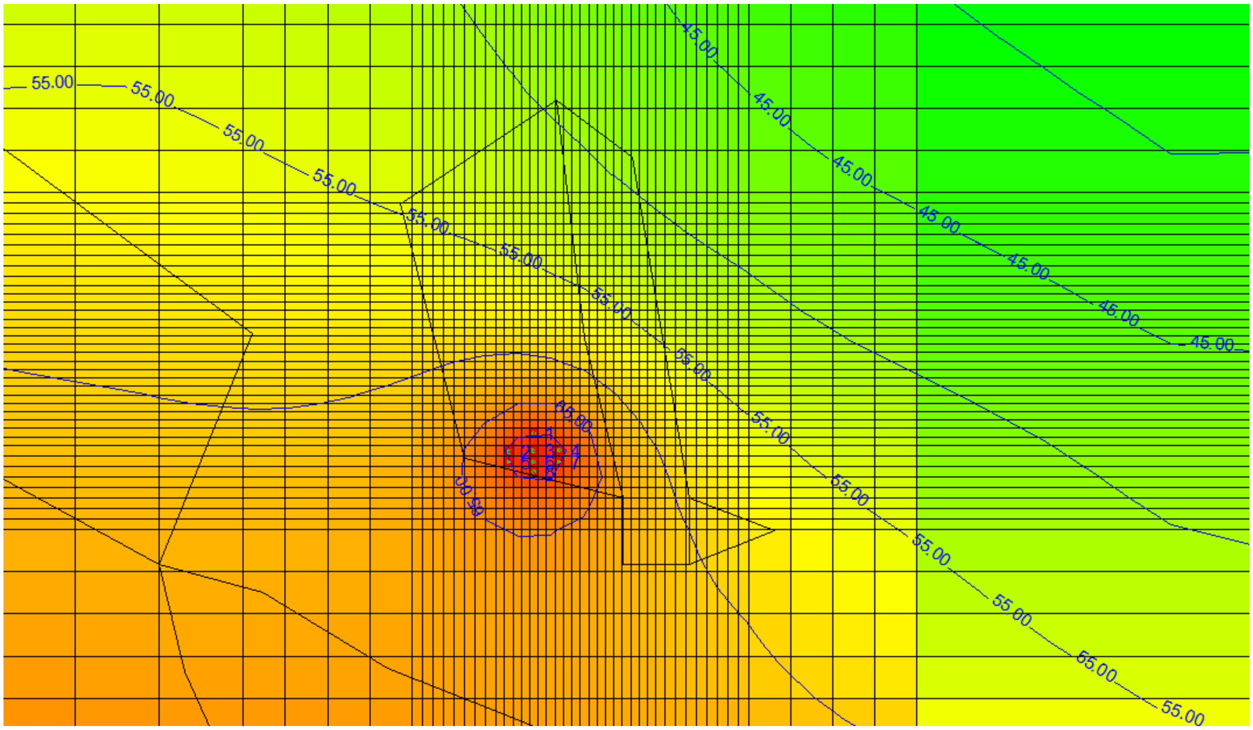
APPENDIX B: MODFLOW AND MT3D RESULTS

RUN 1 MODFLOW

Stress Period (1-12)



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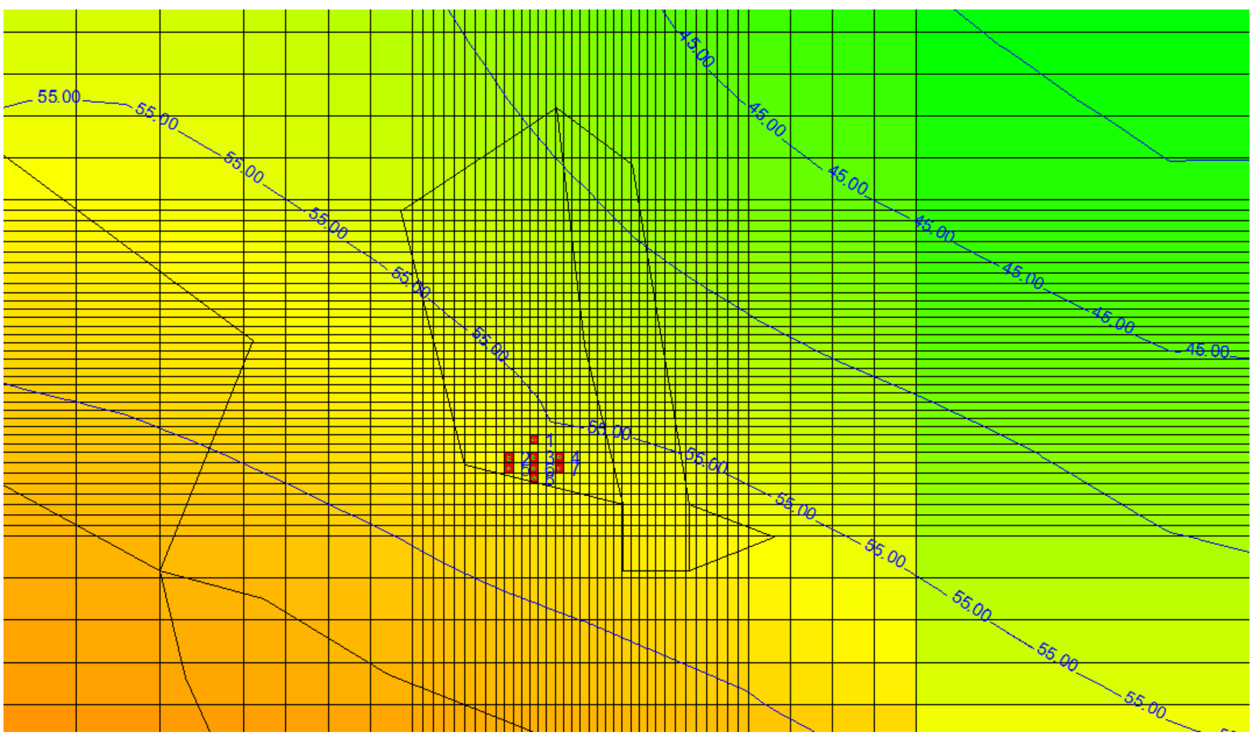
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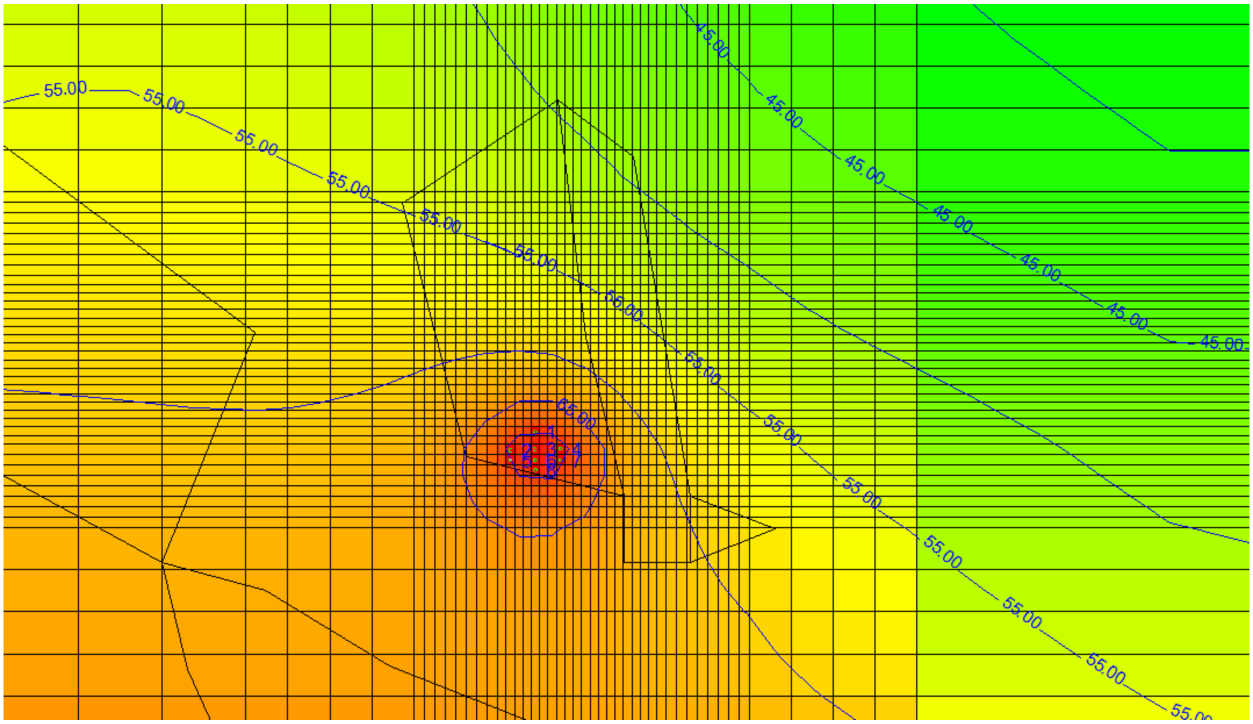
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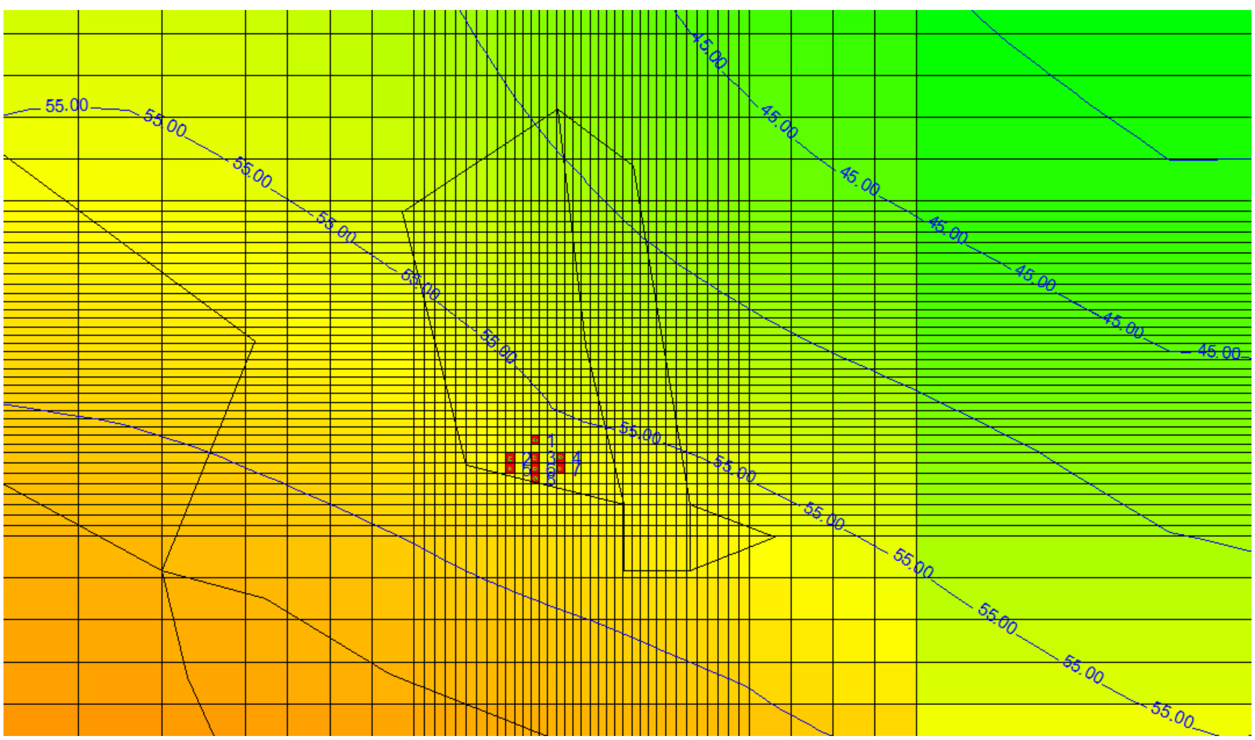
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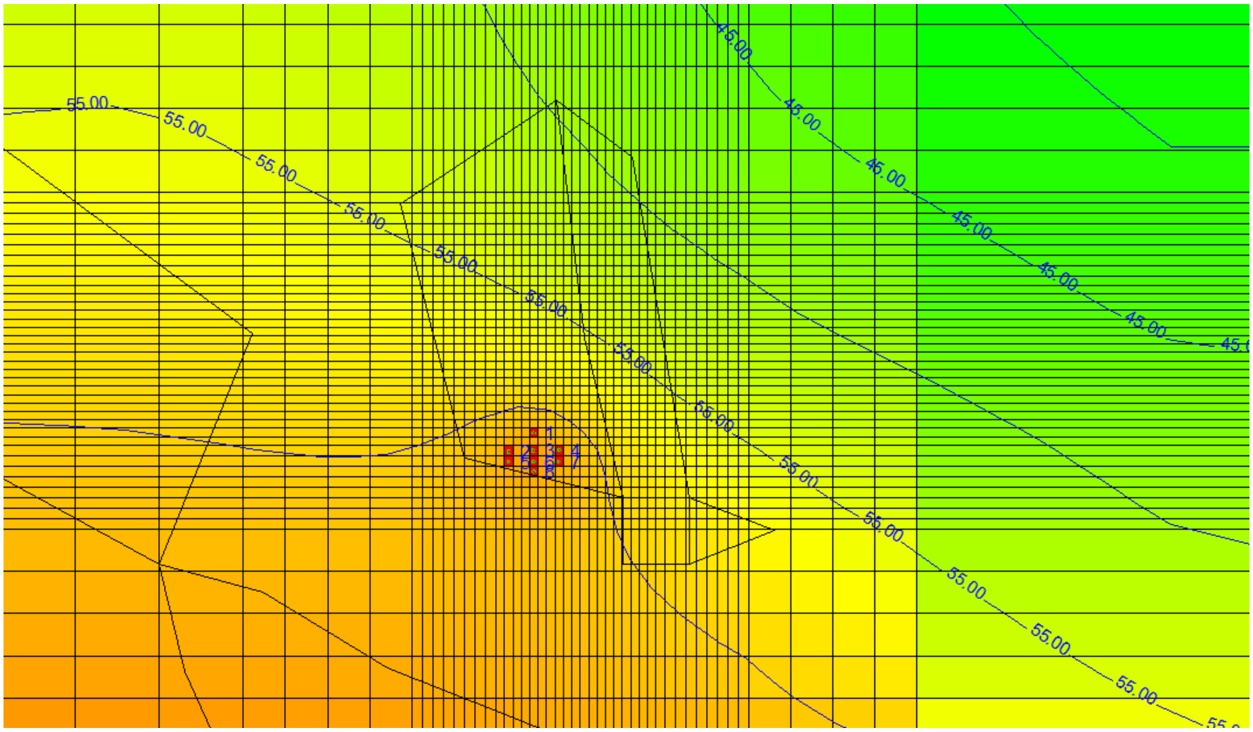

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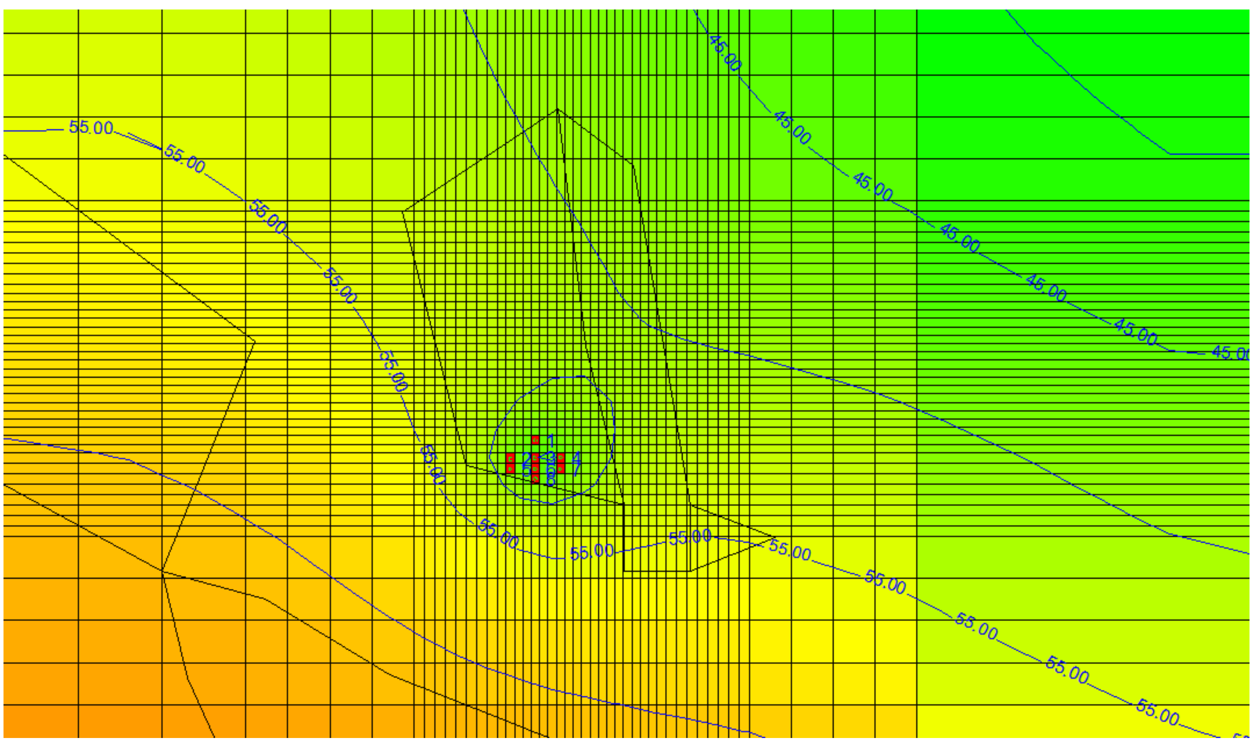

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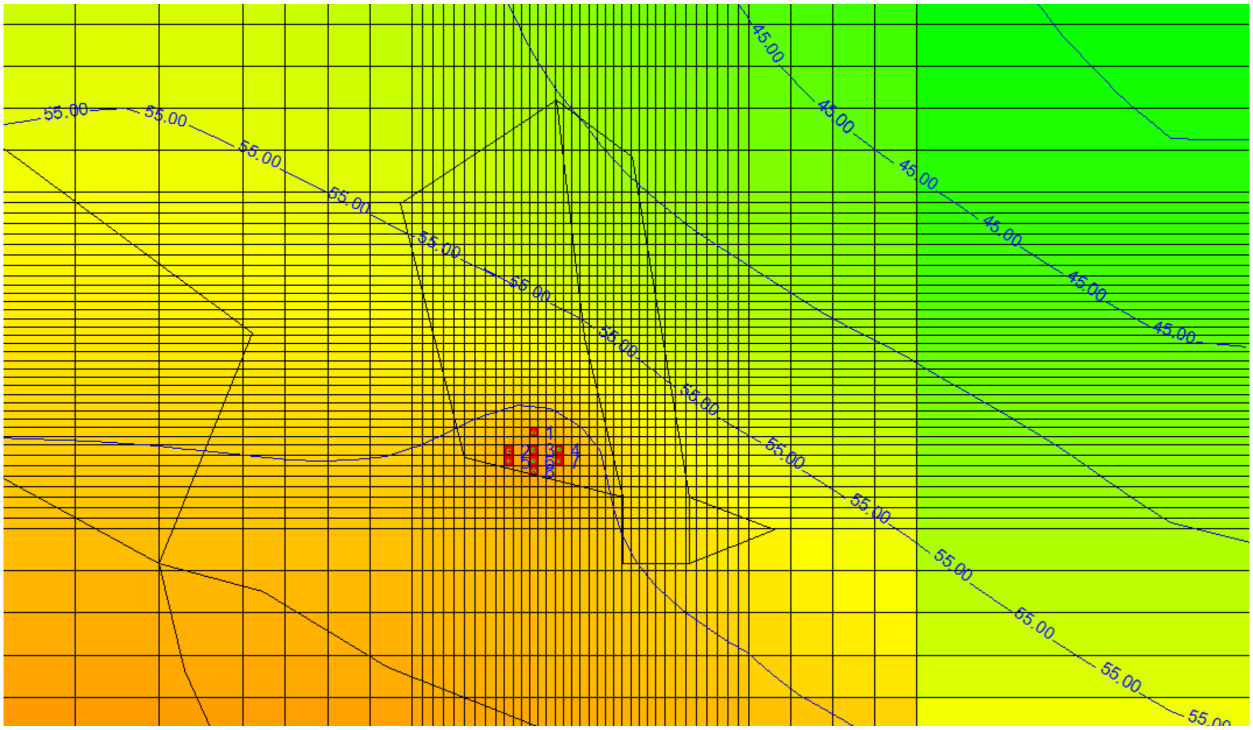
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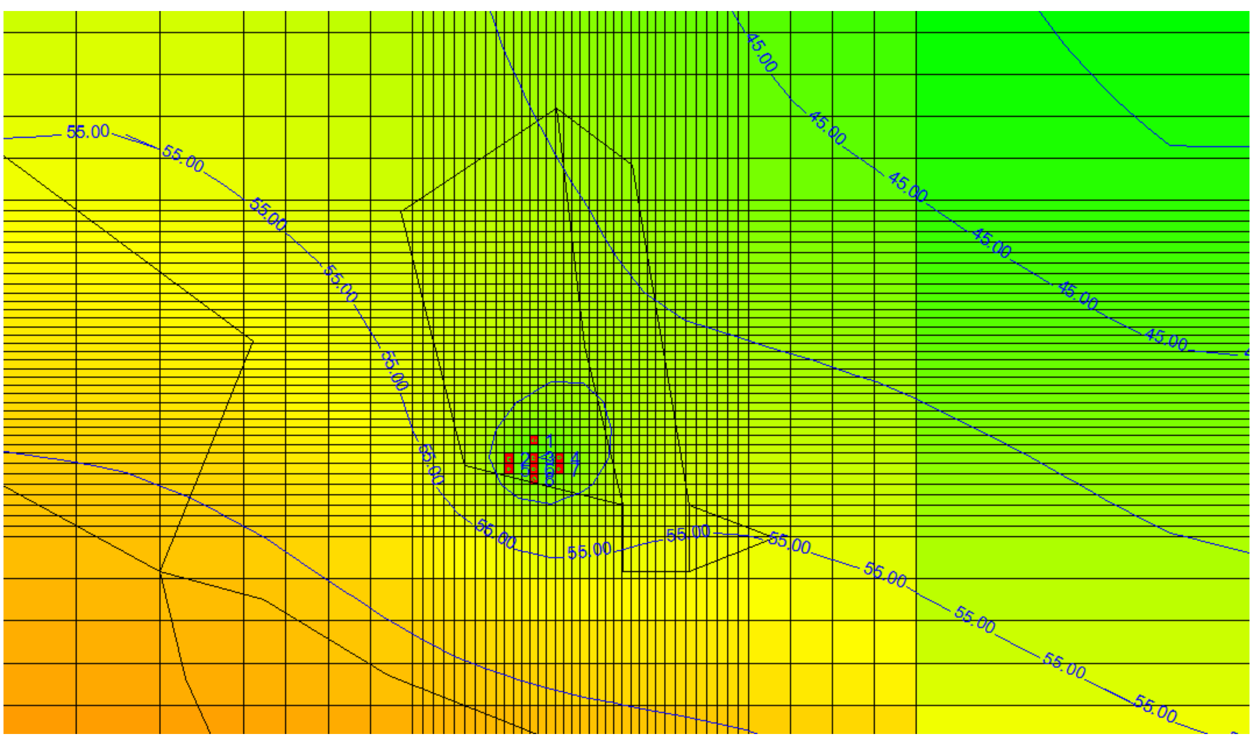
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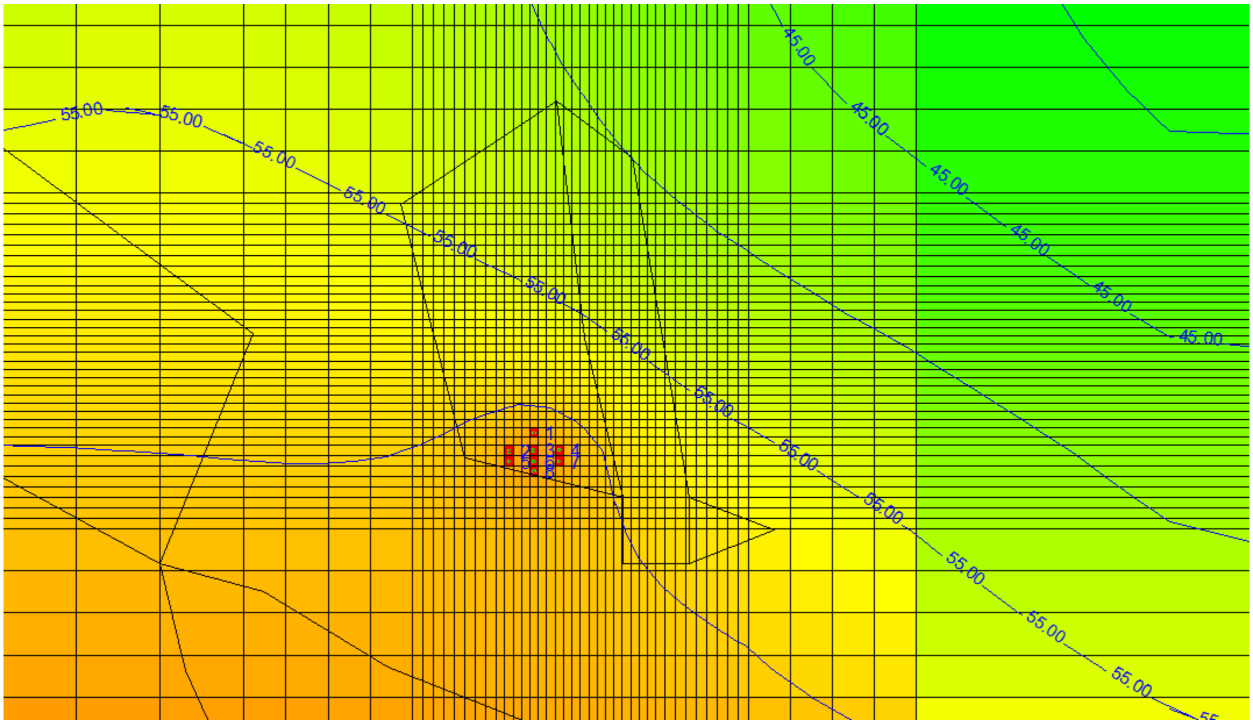
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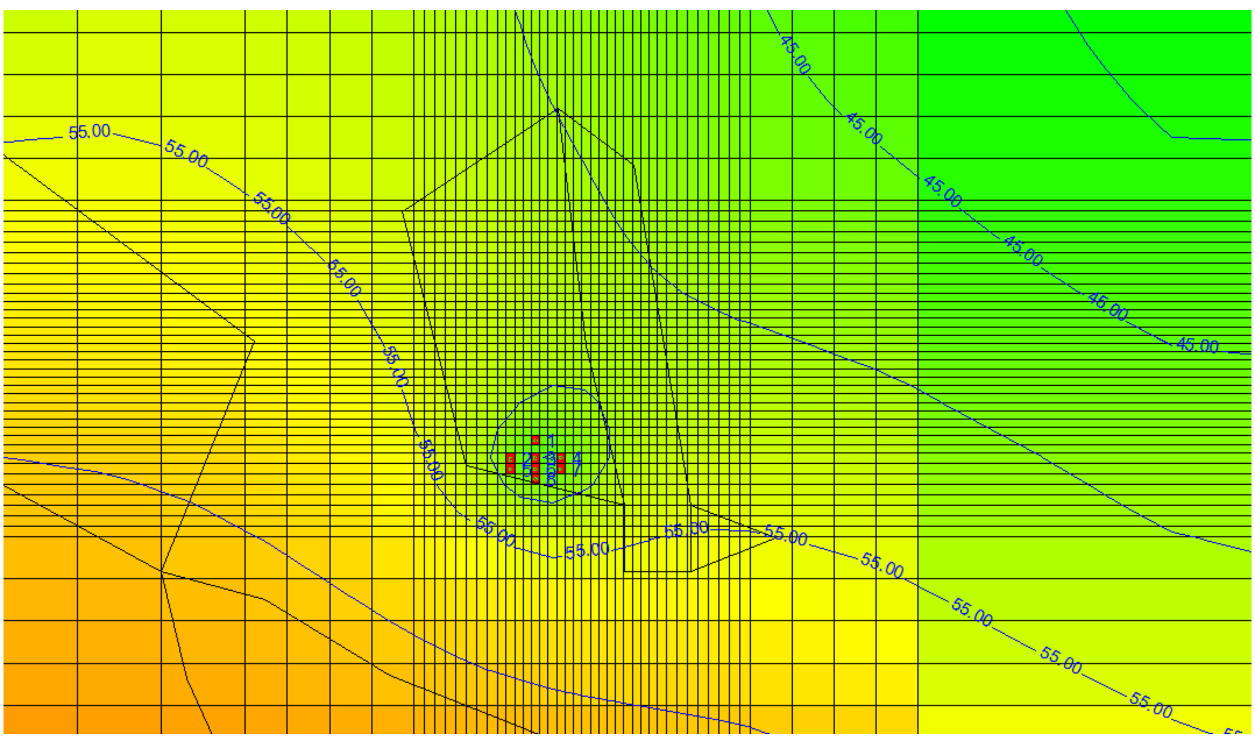
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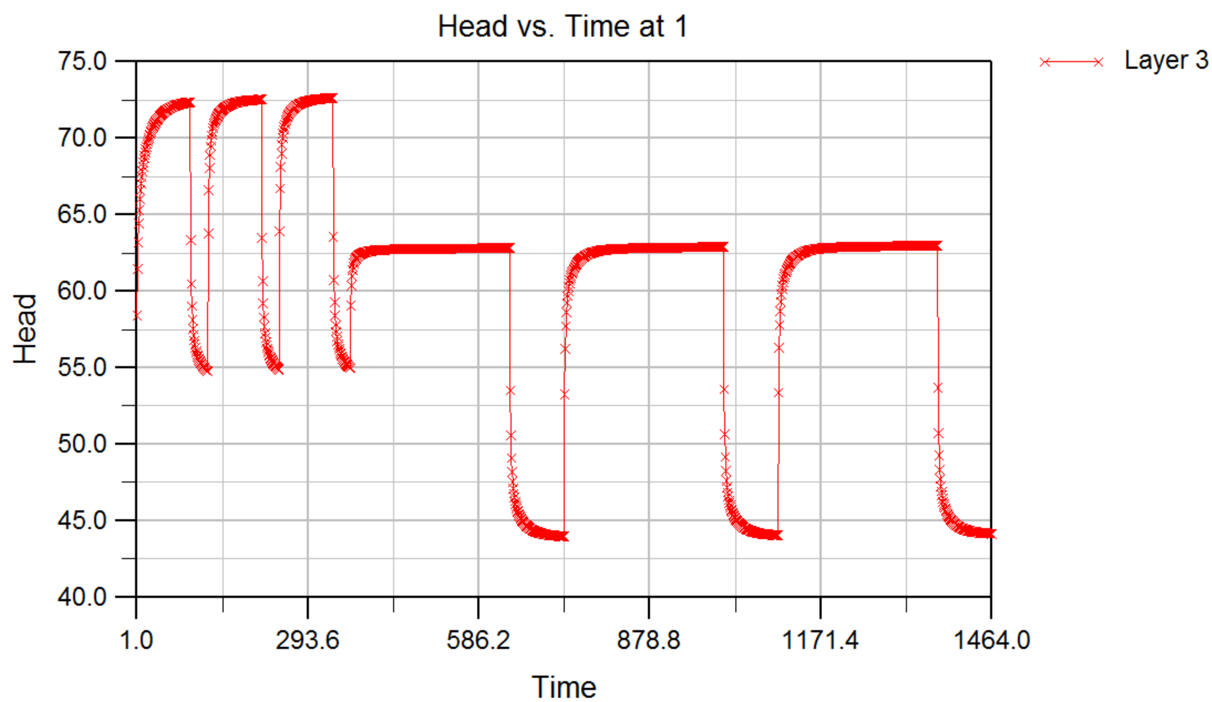
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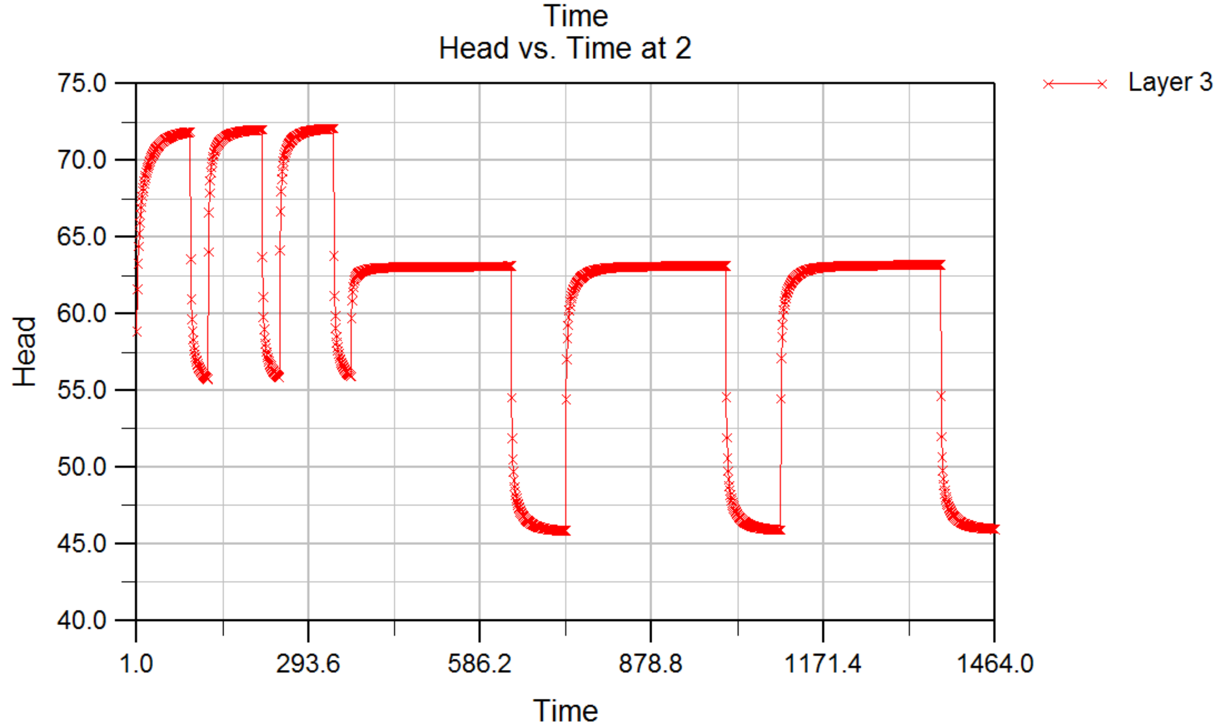
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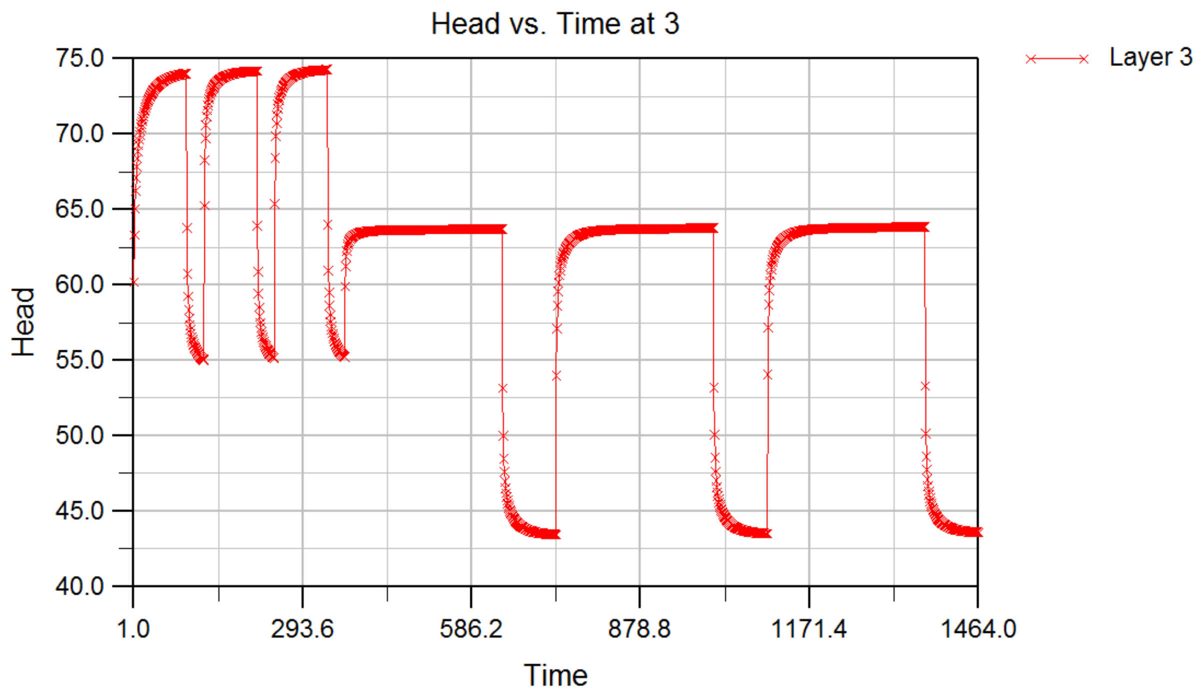

Head vs. Time at 3
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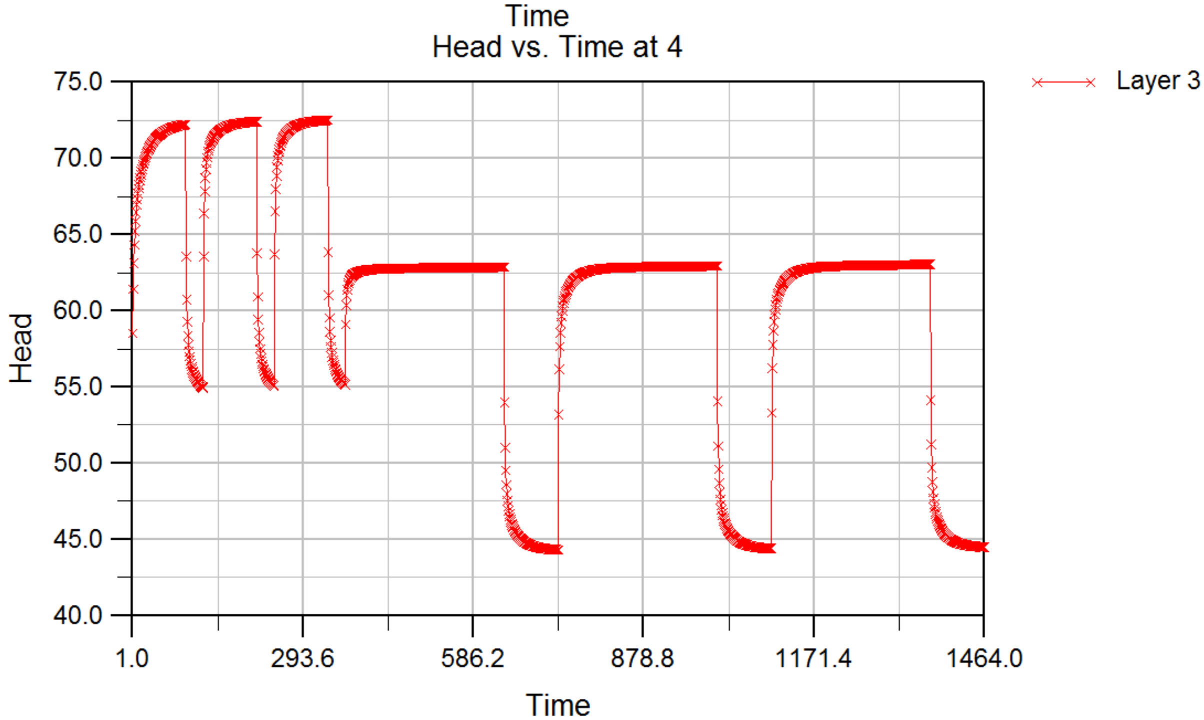

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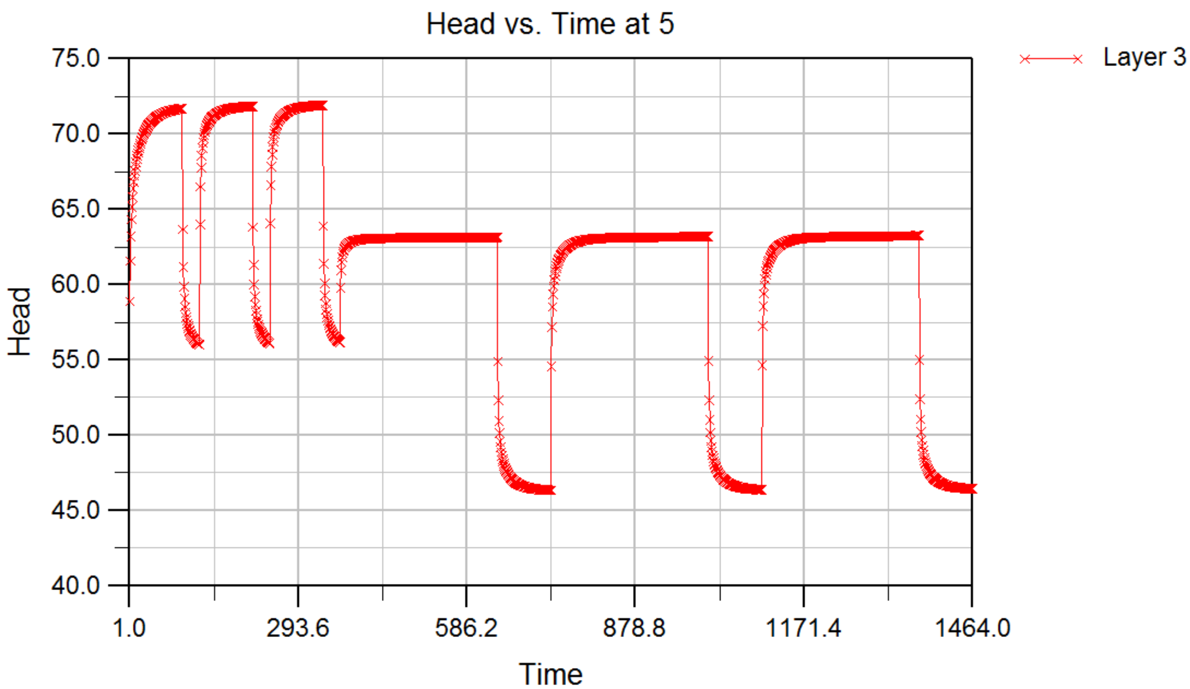
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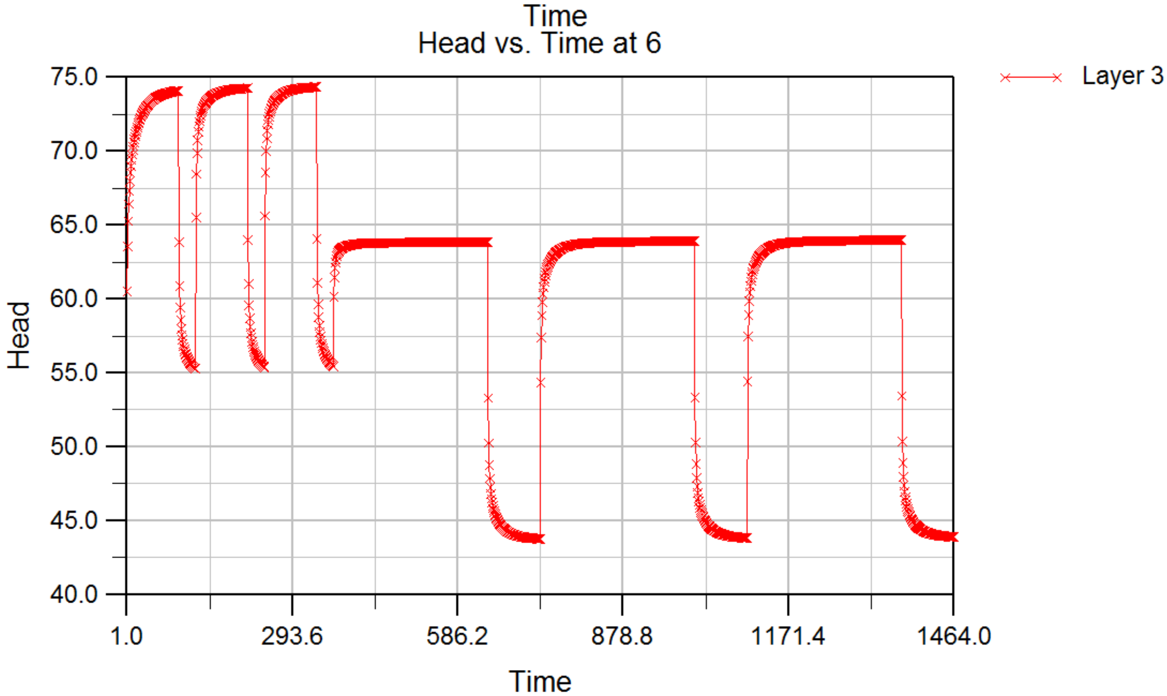
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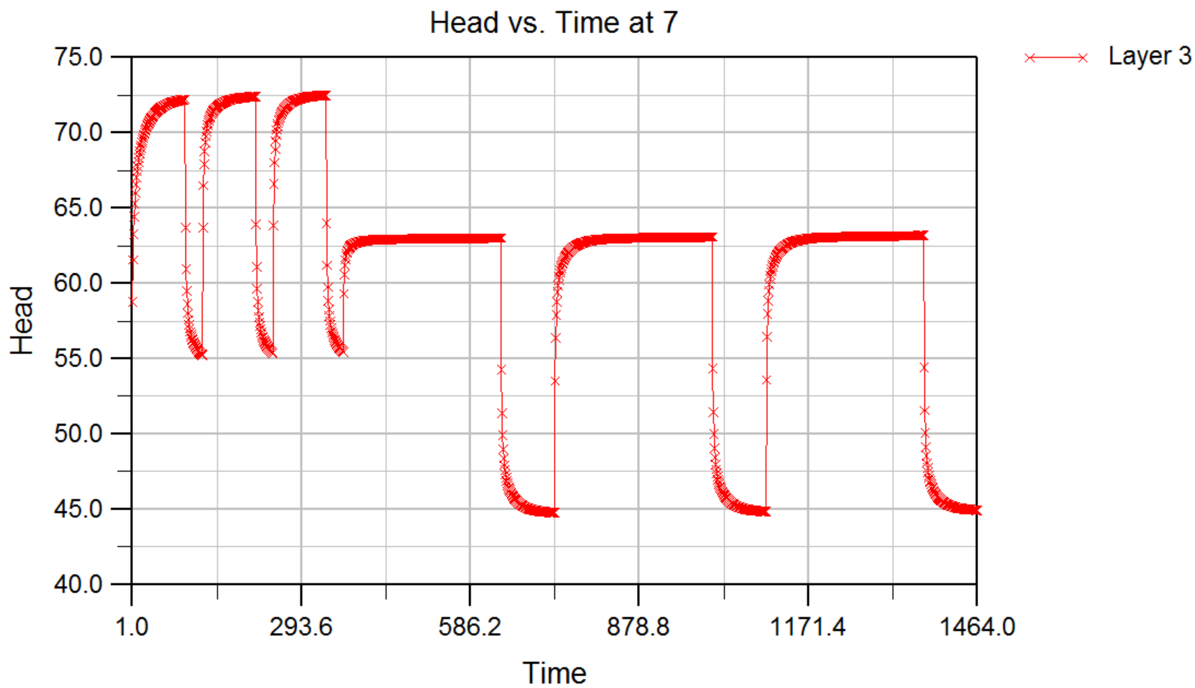
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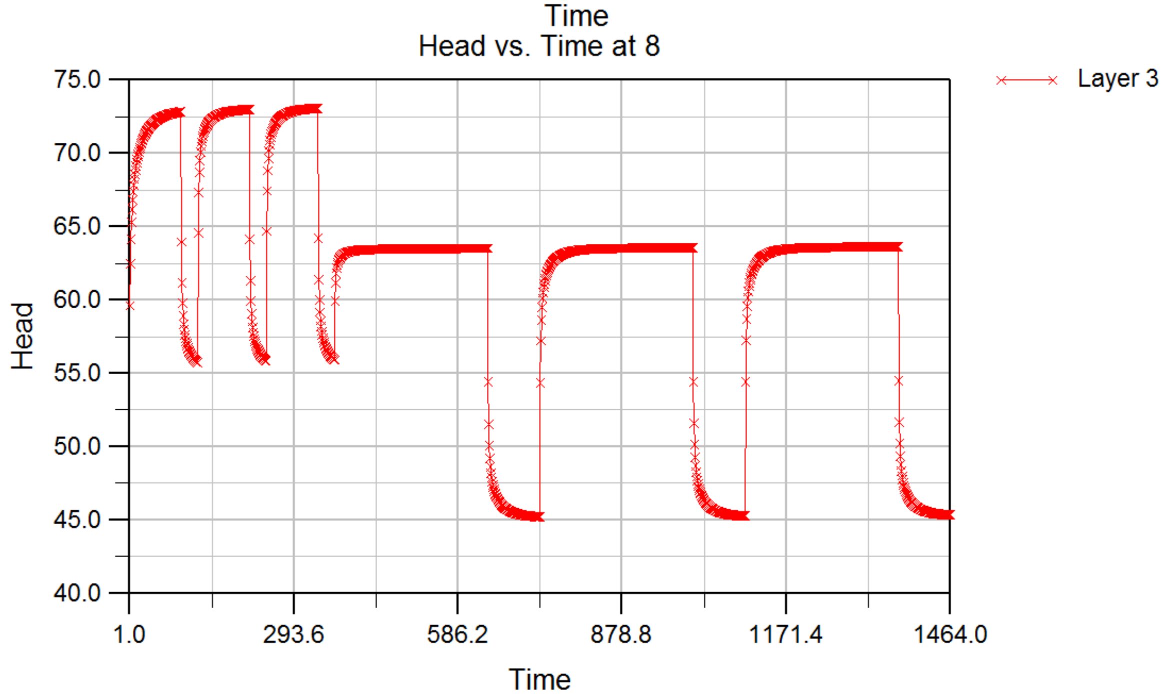
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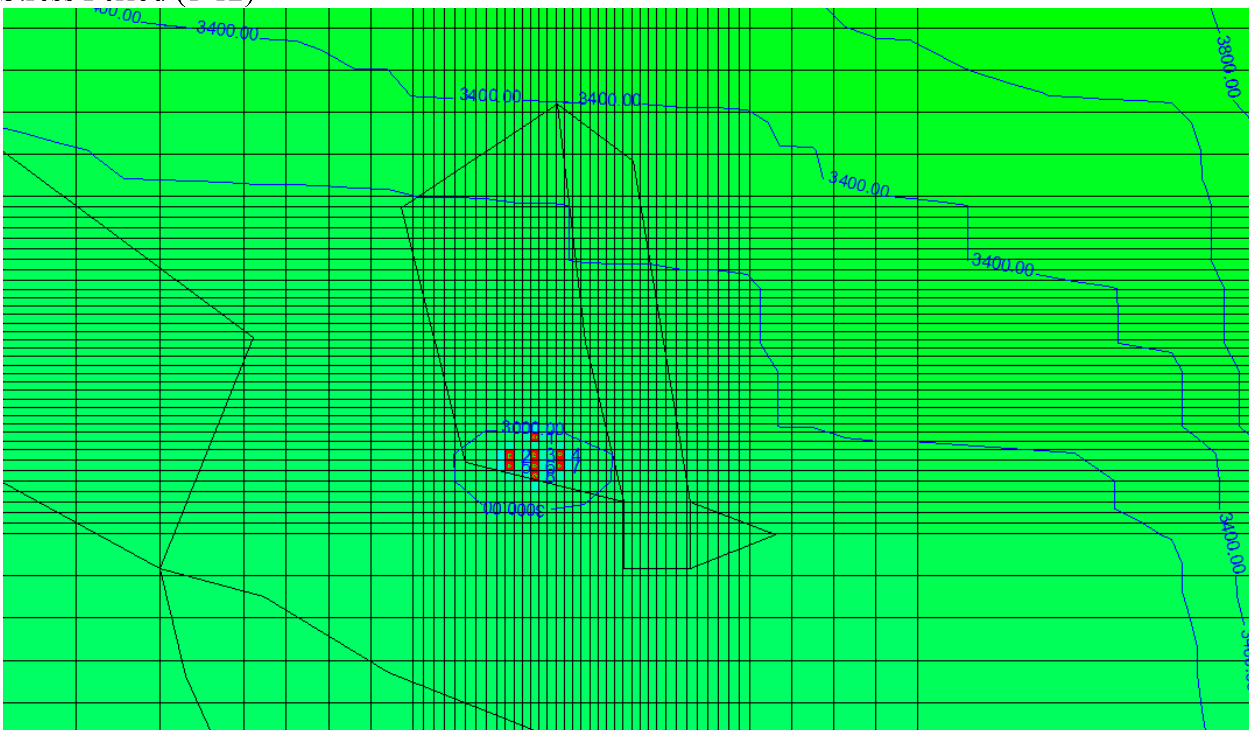
RUN 1 MT3D 1

Stress Period (1-12)



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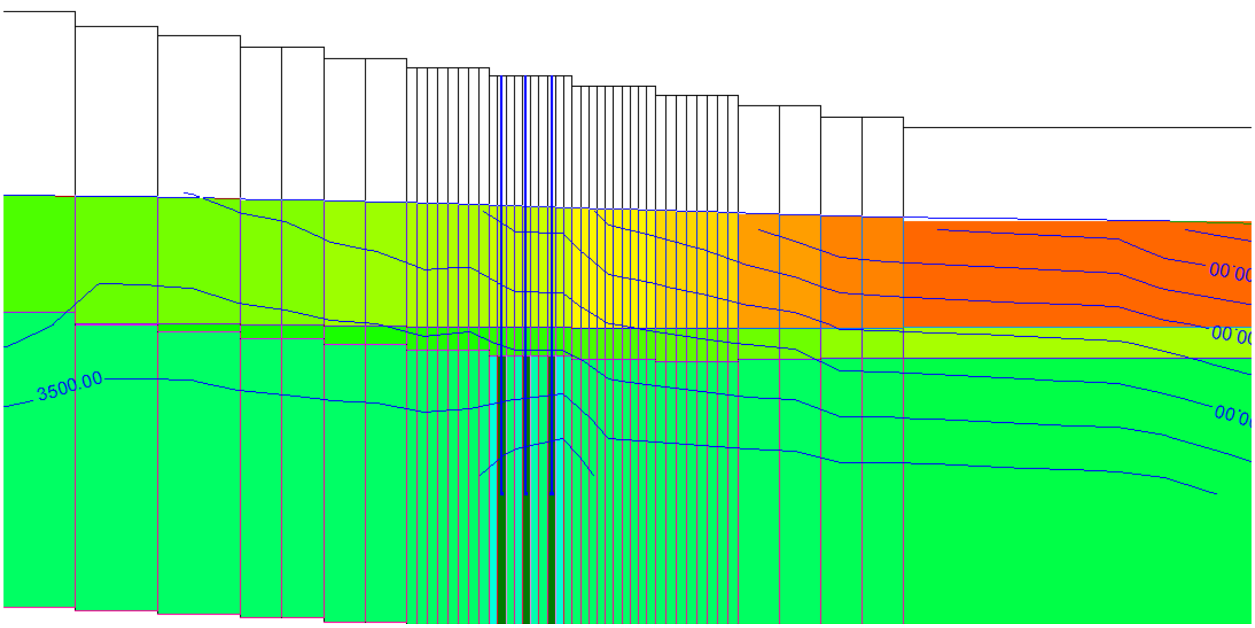

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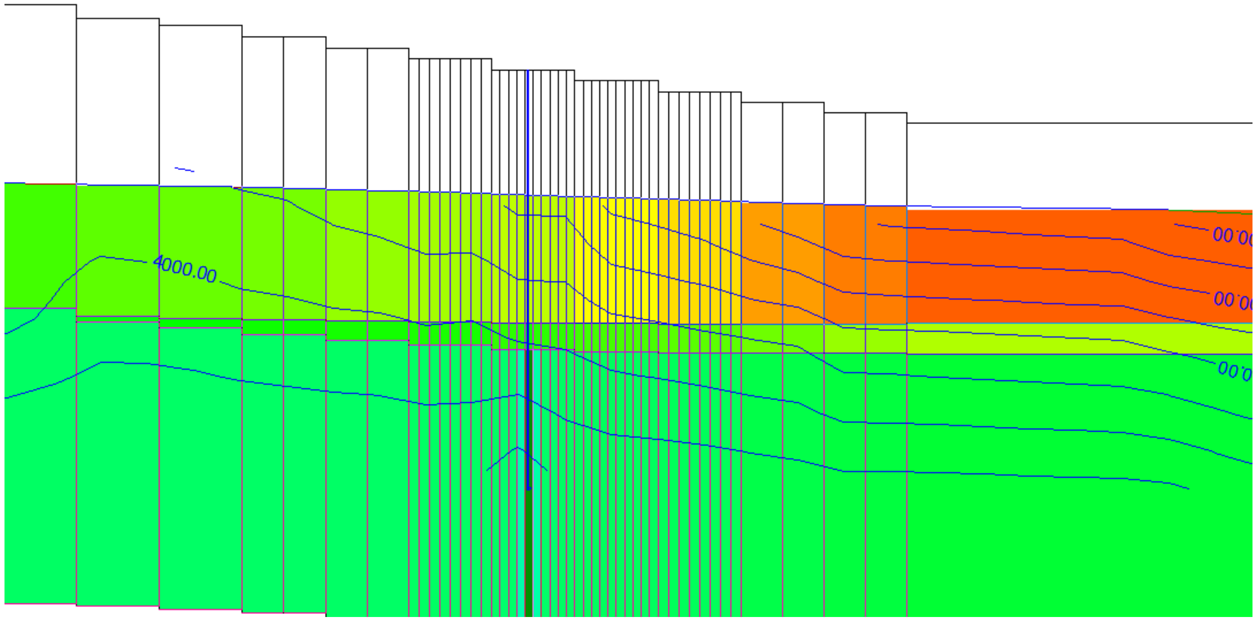

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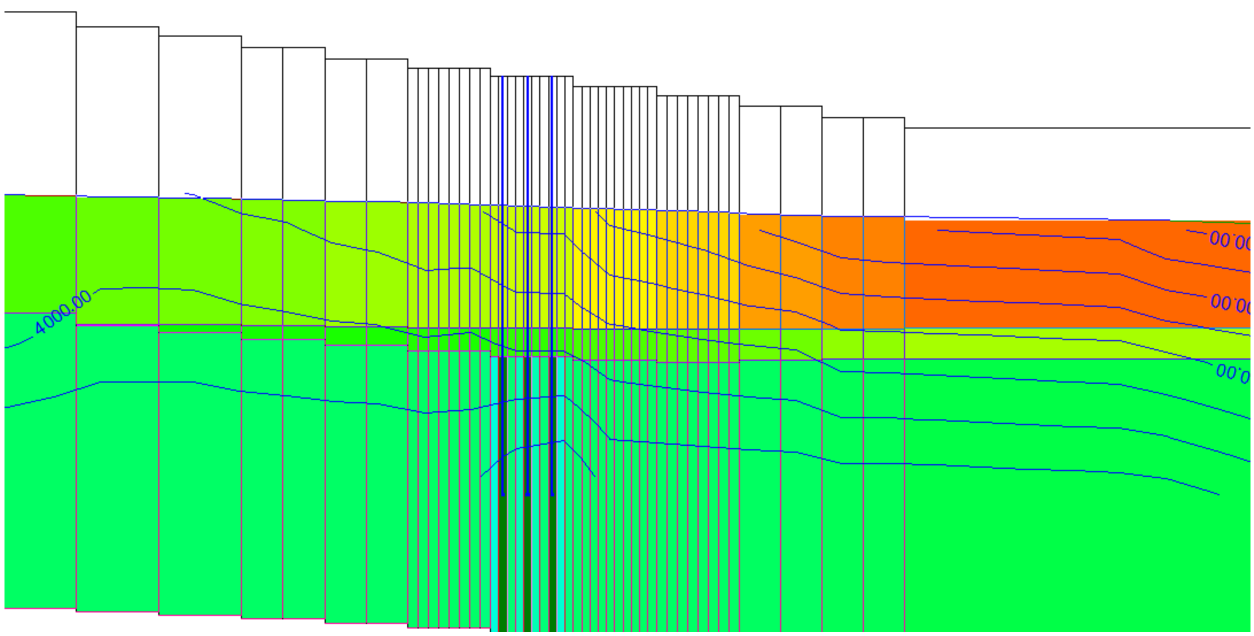

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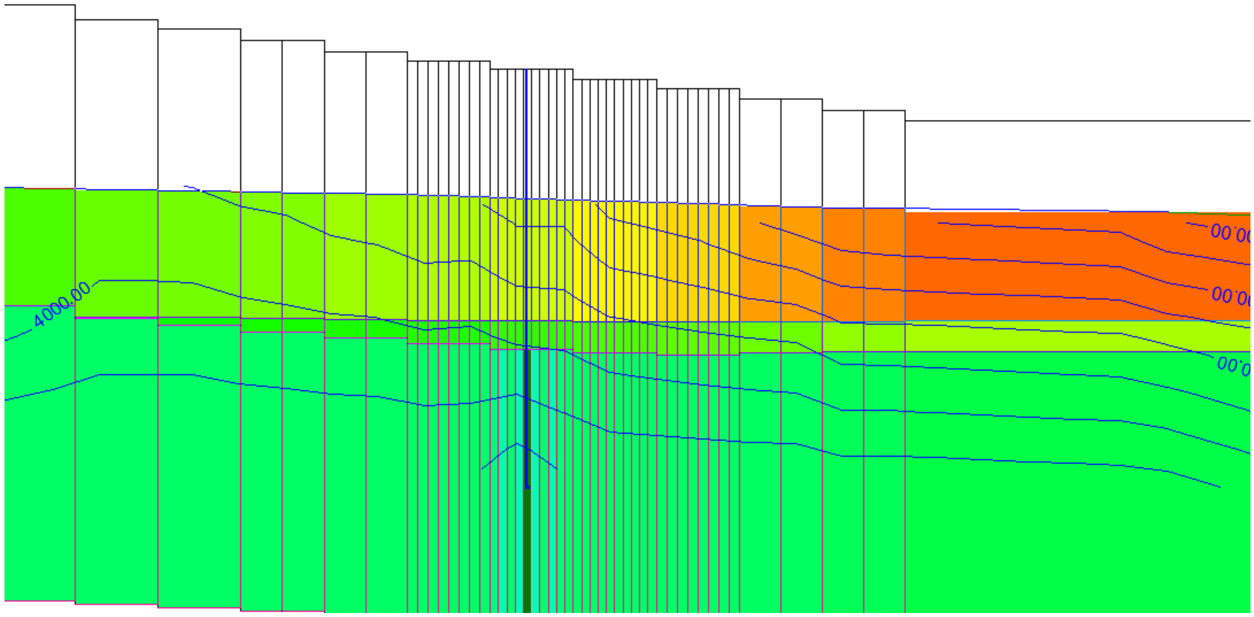

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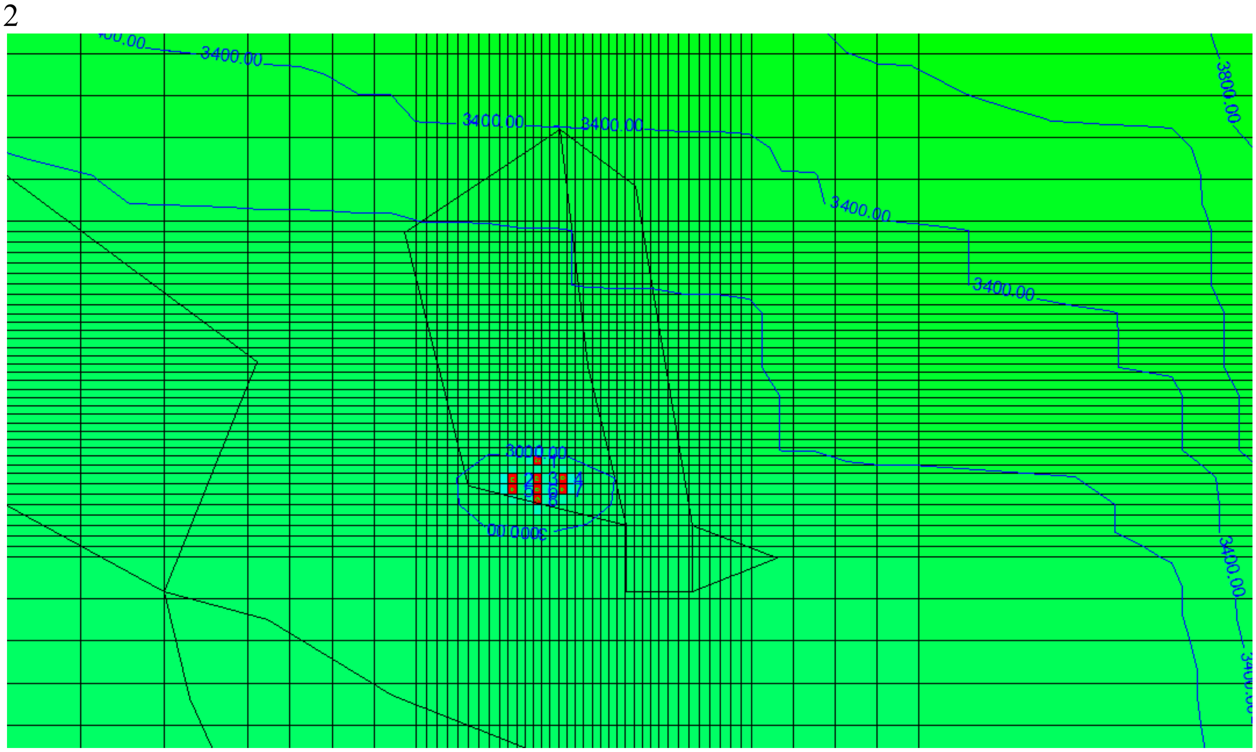

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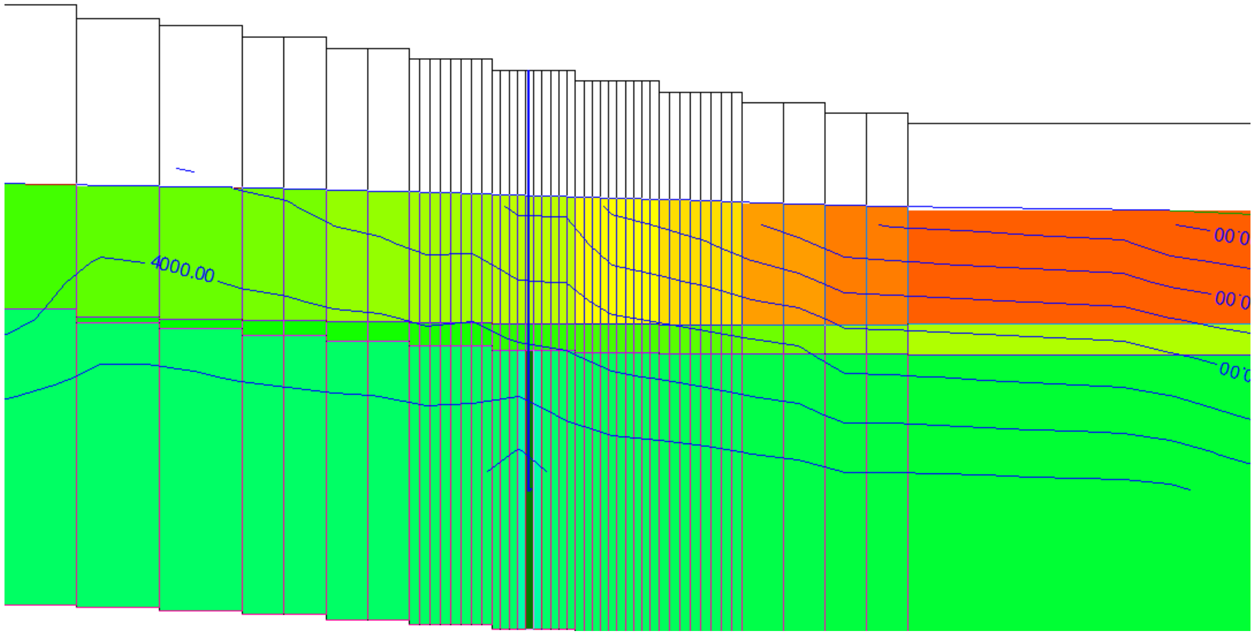

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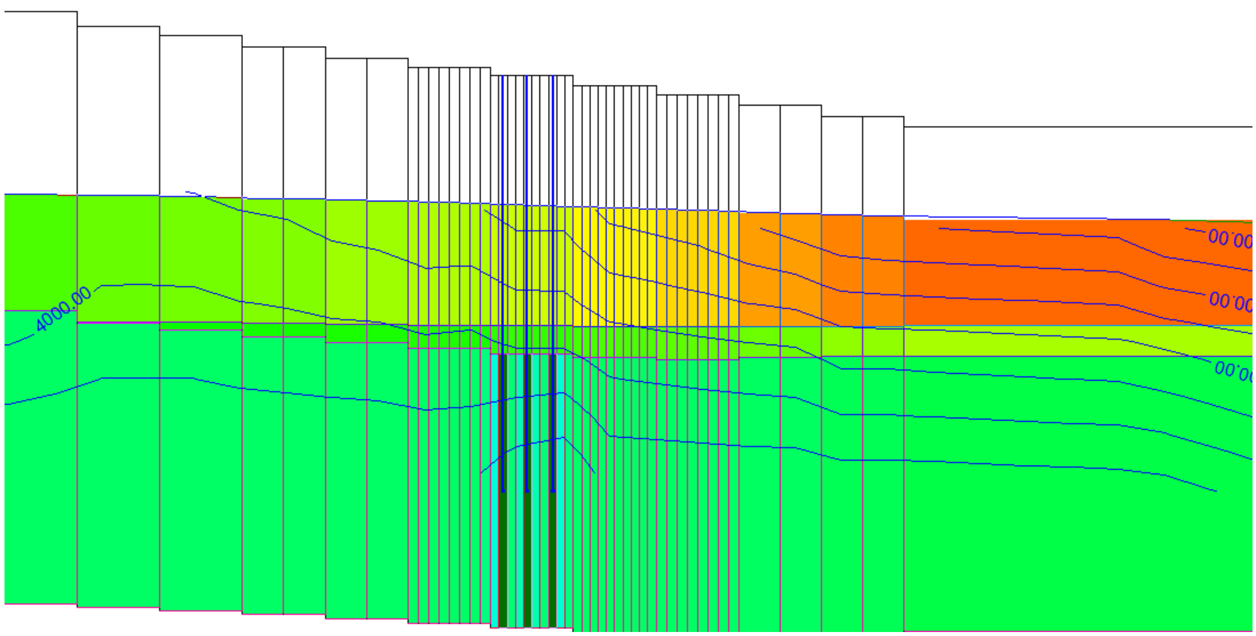

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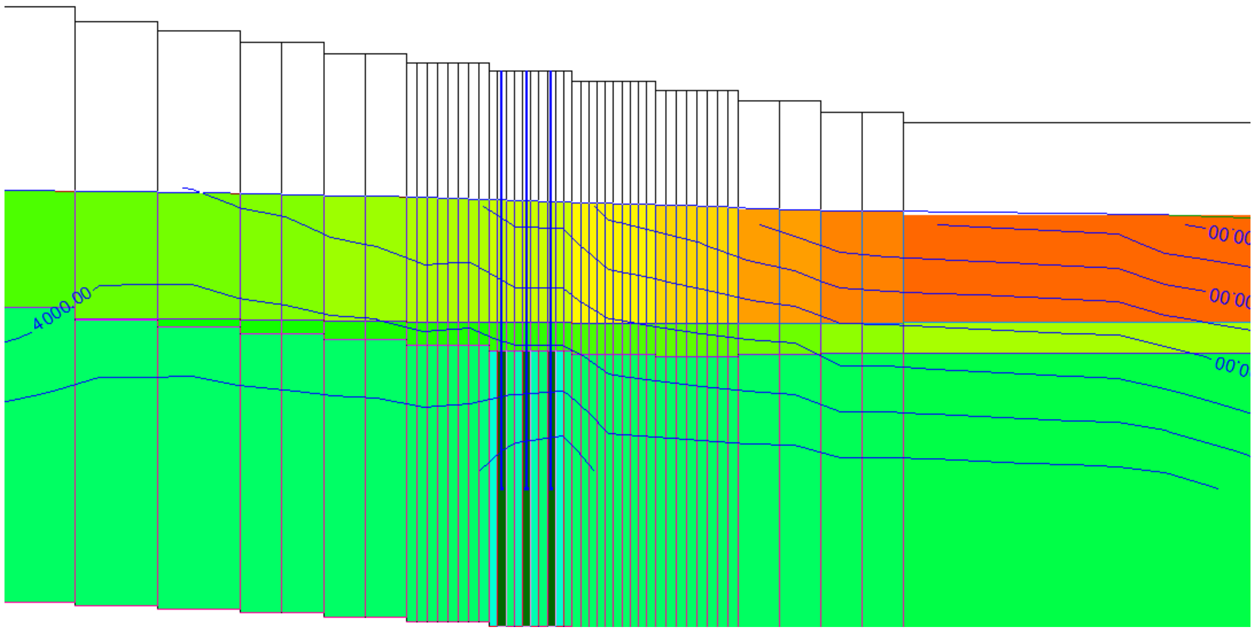

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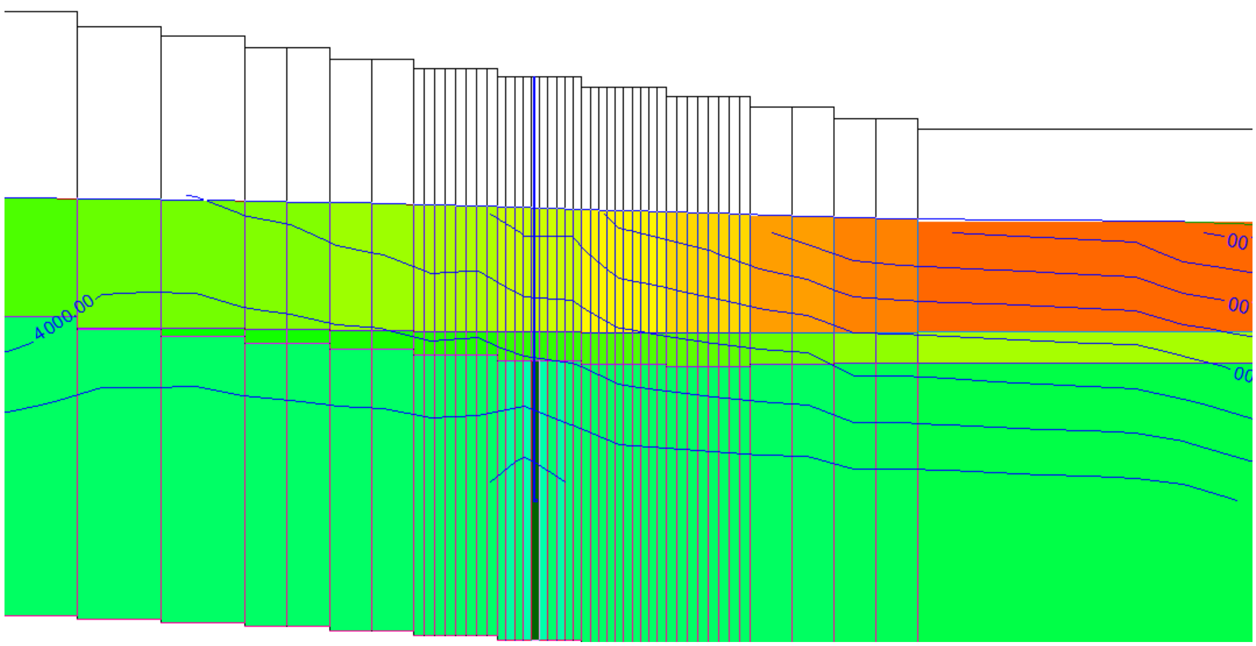

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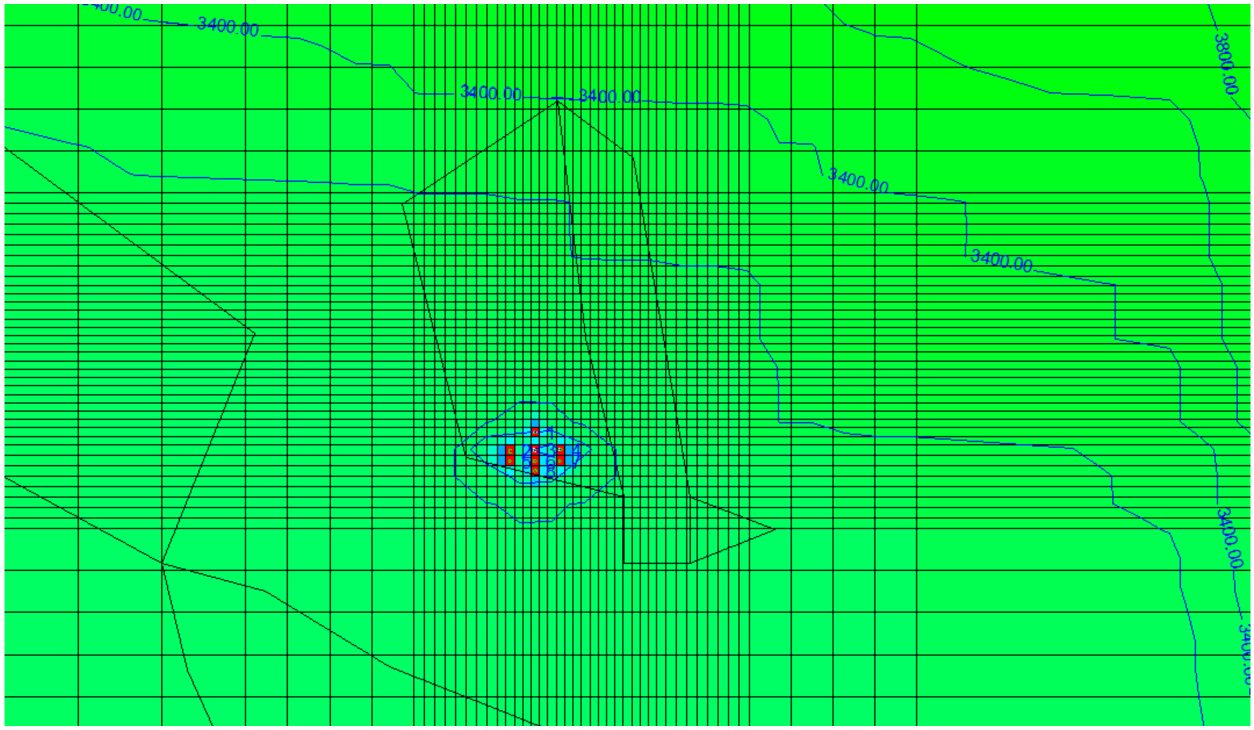

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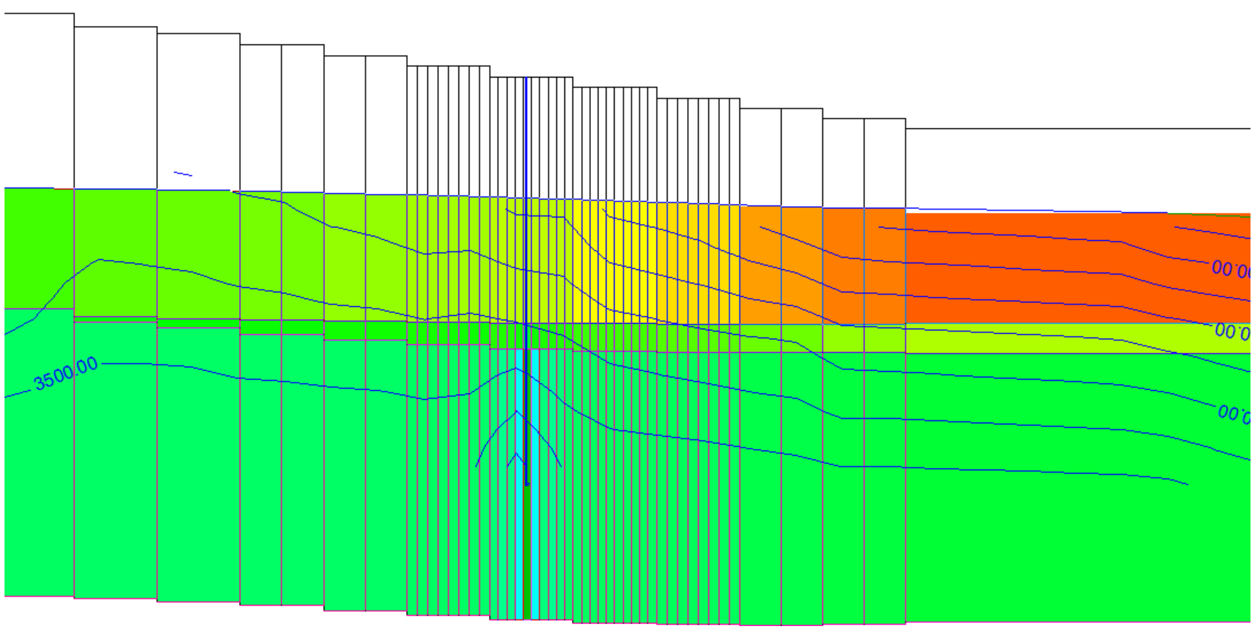

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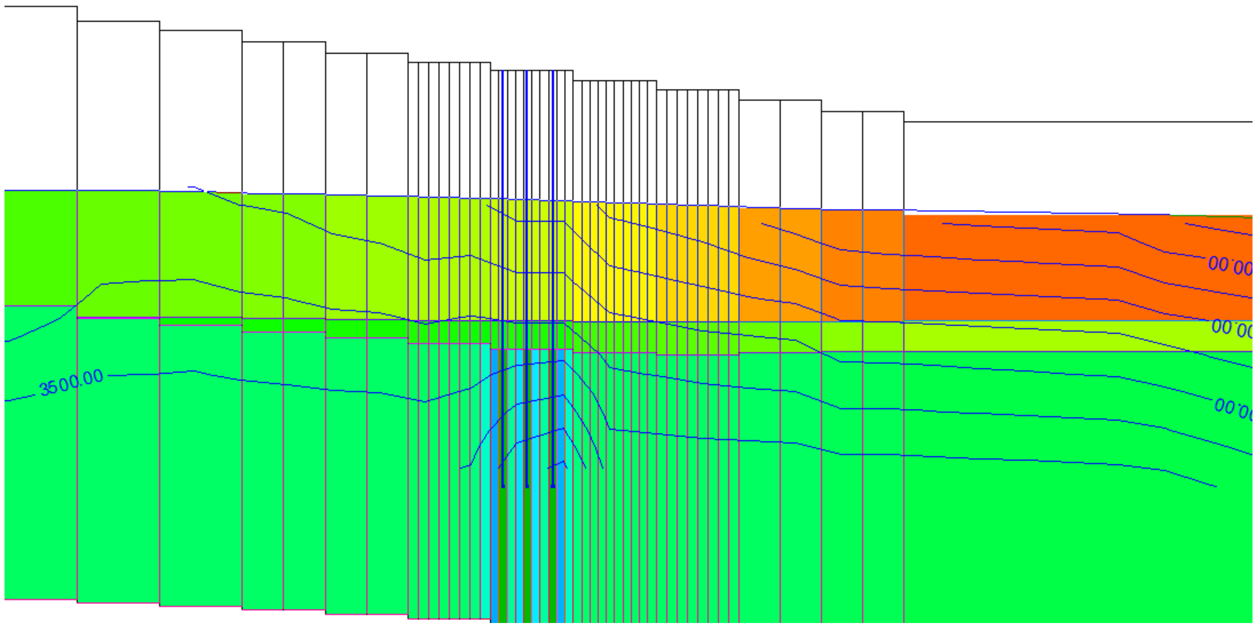

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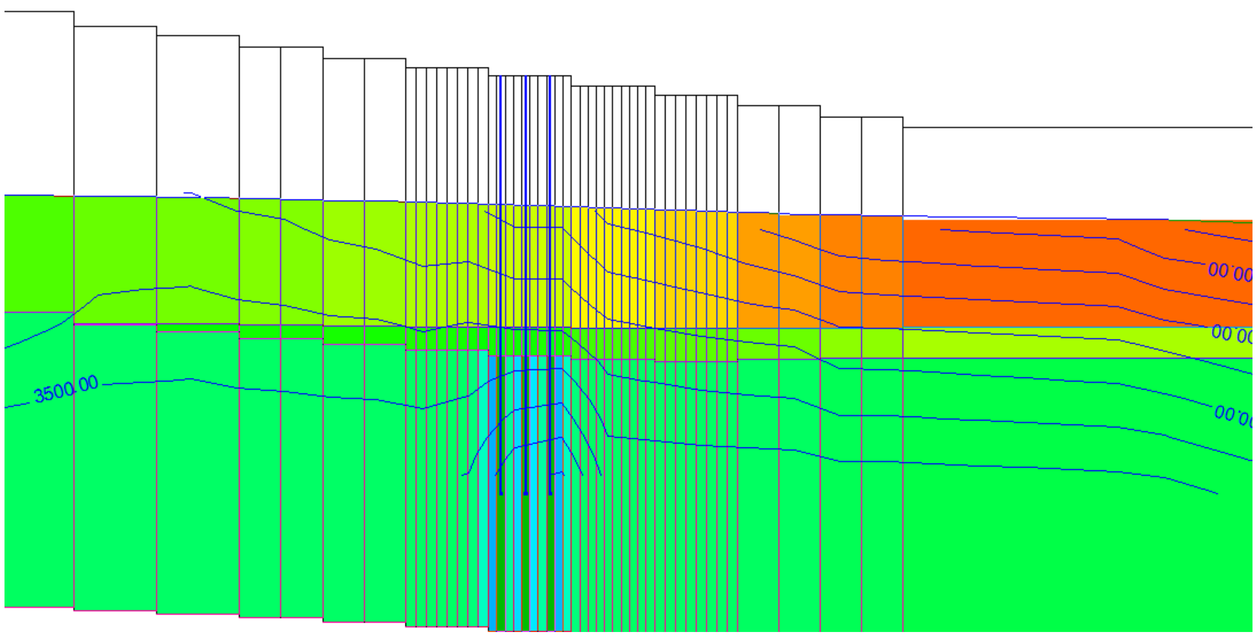

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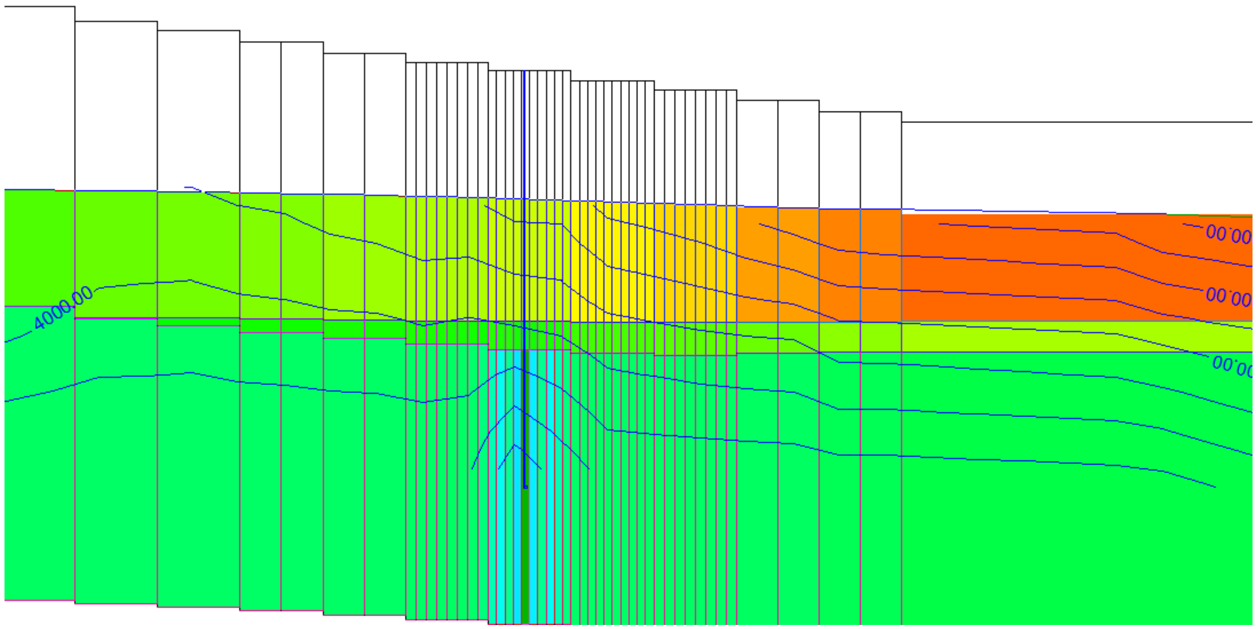

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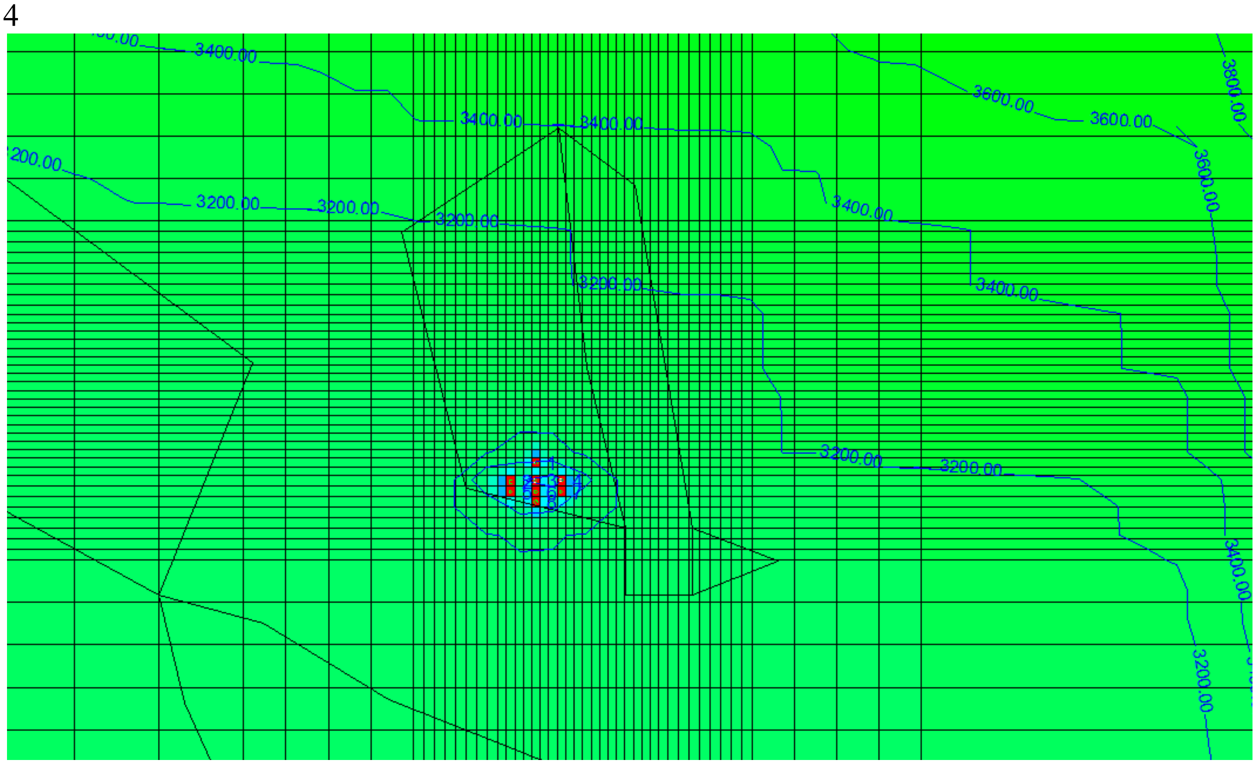

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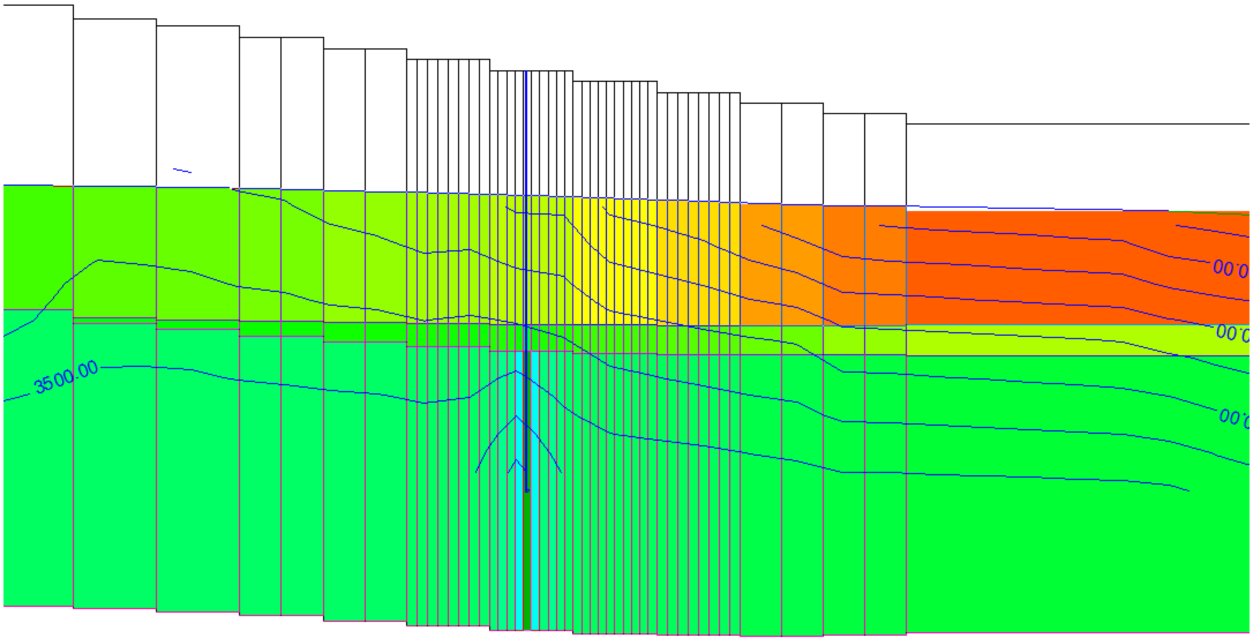

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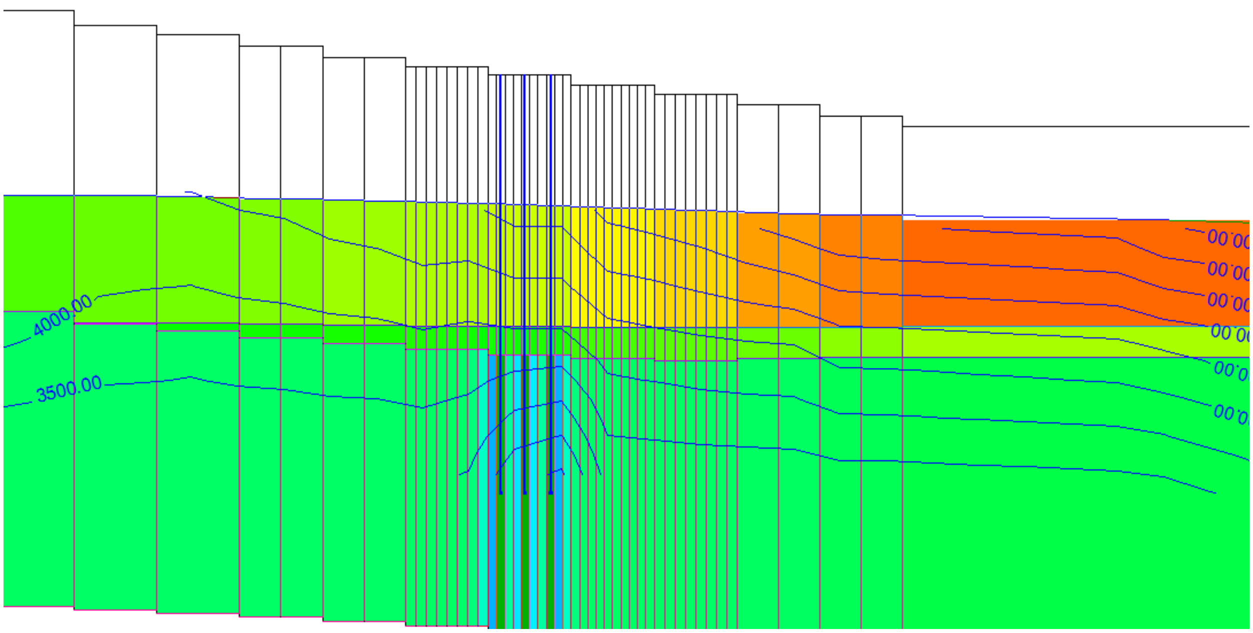

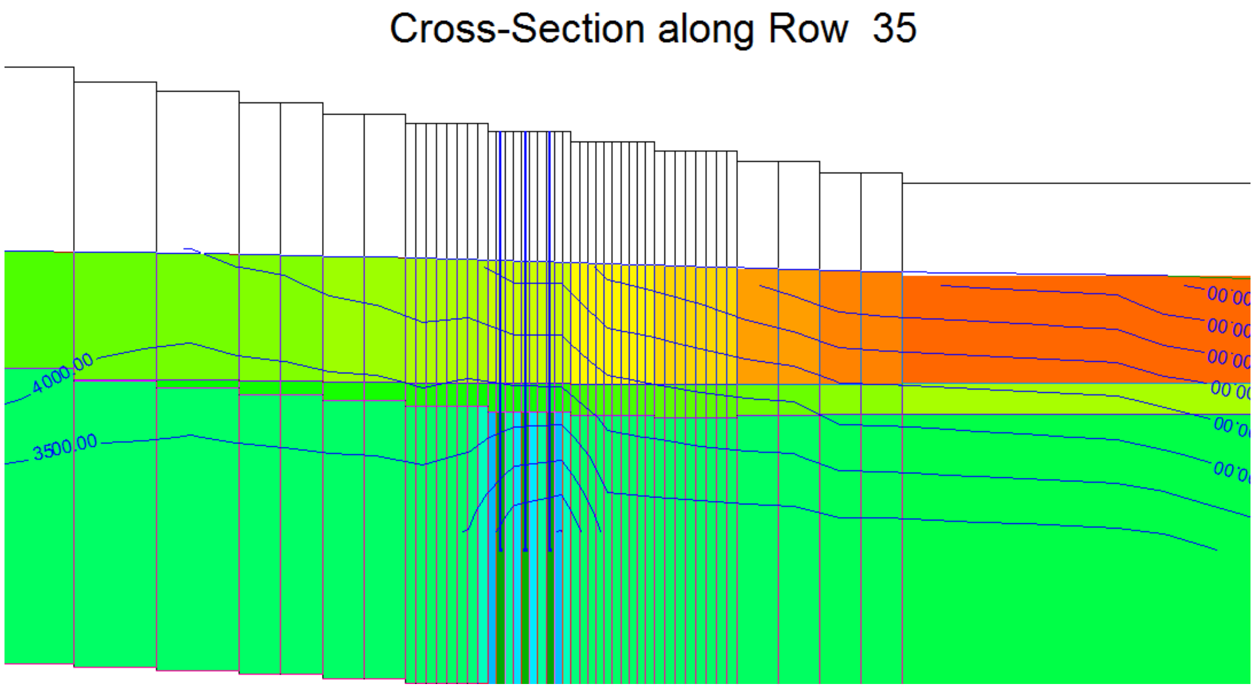
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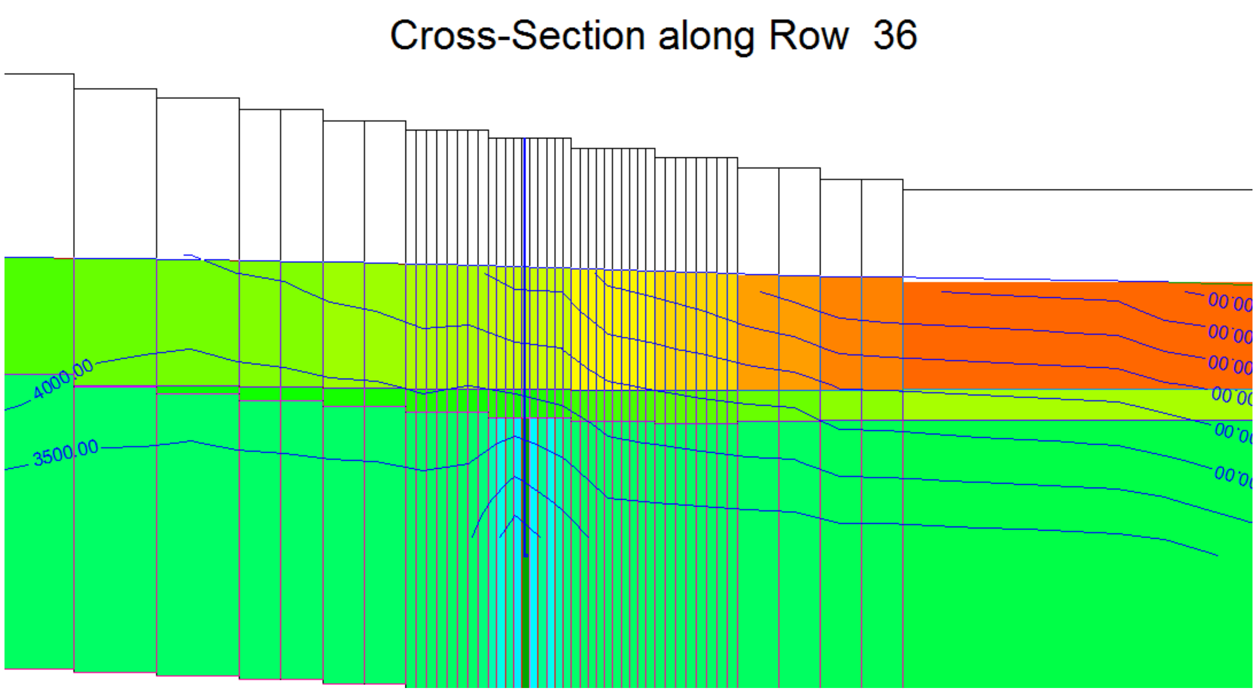
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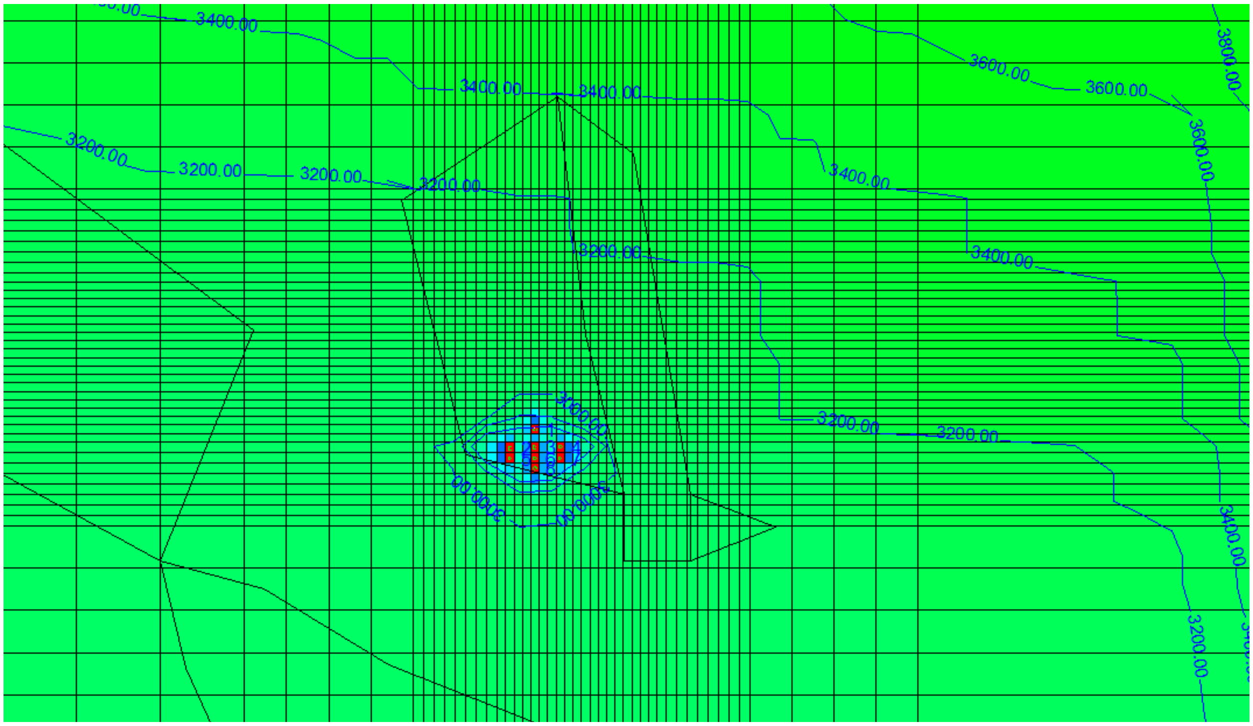

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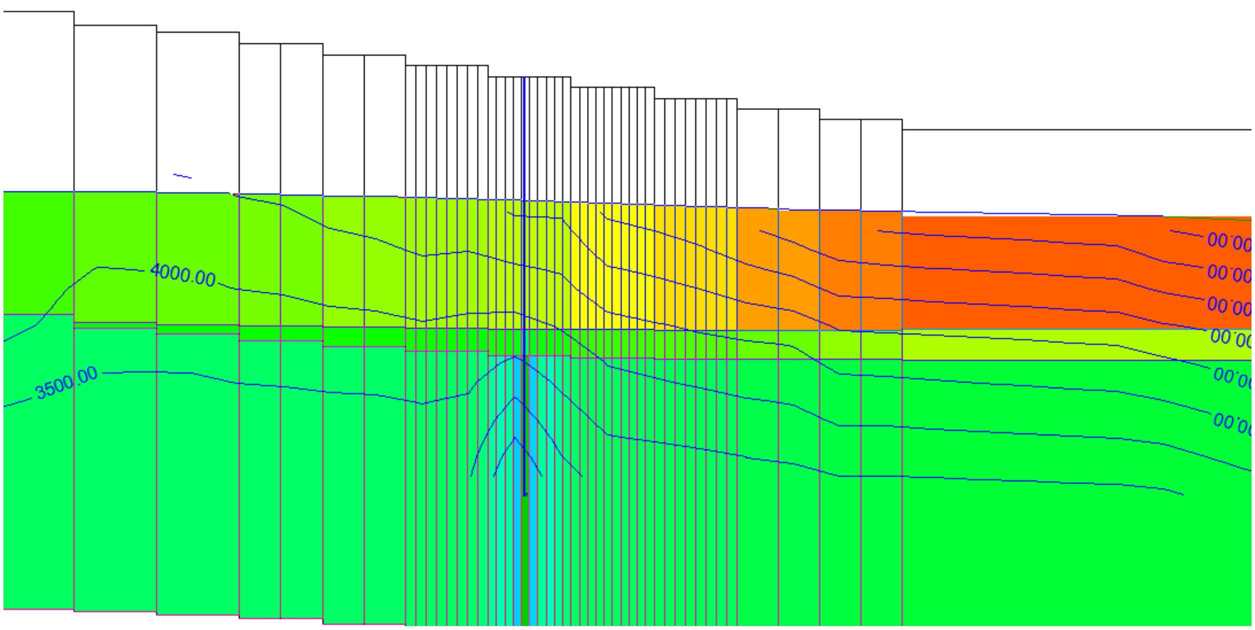

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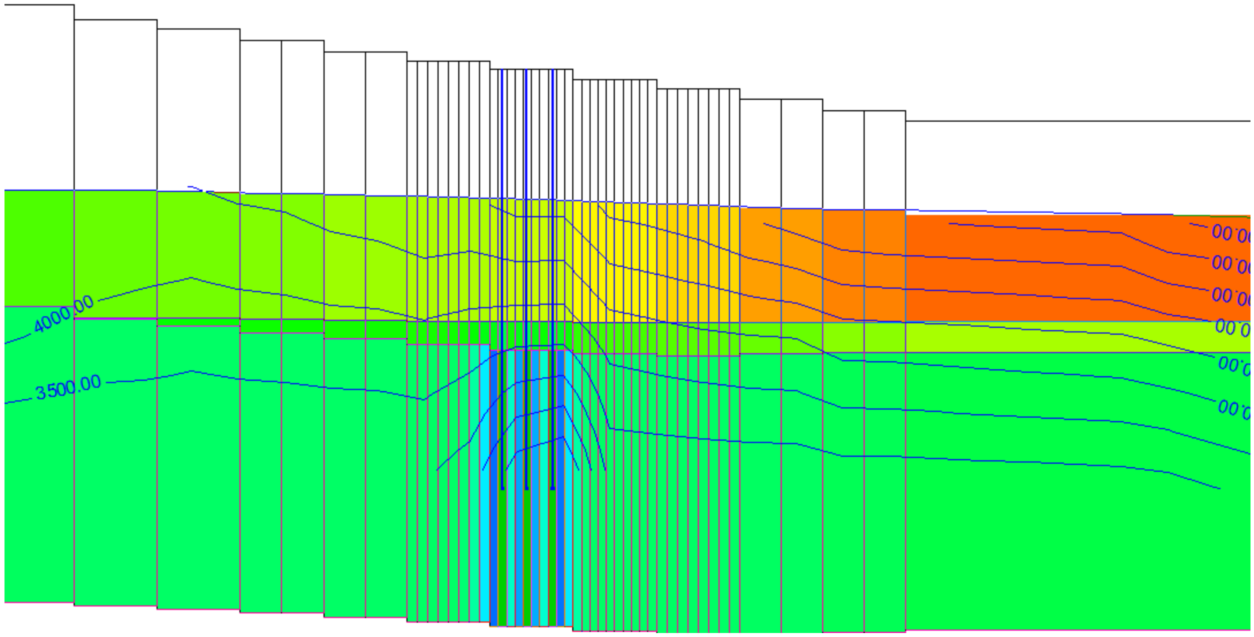

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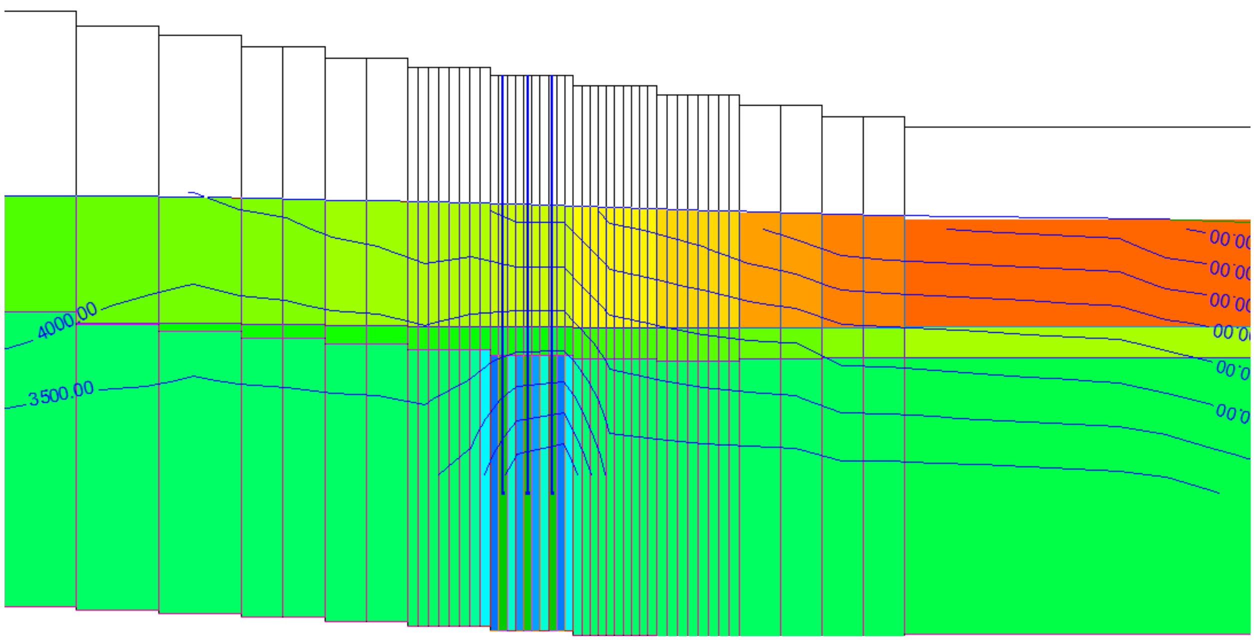

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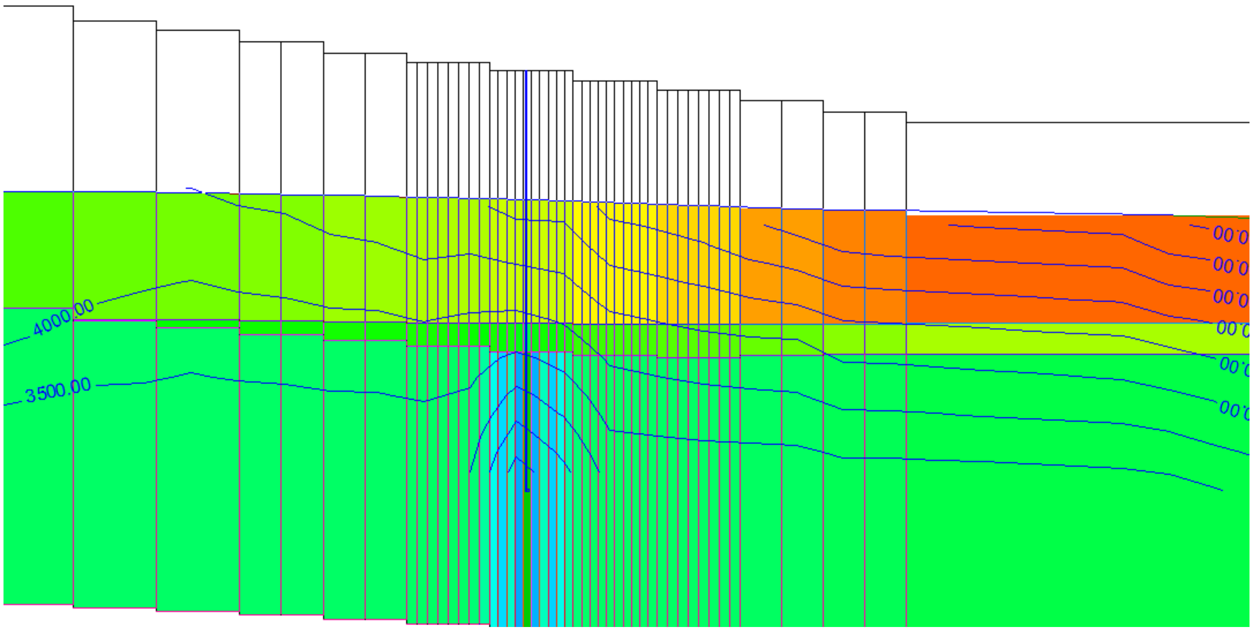

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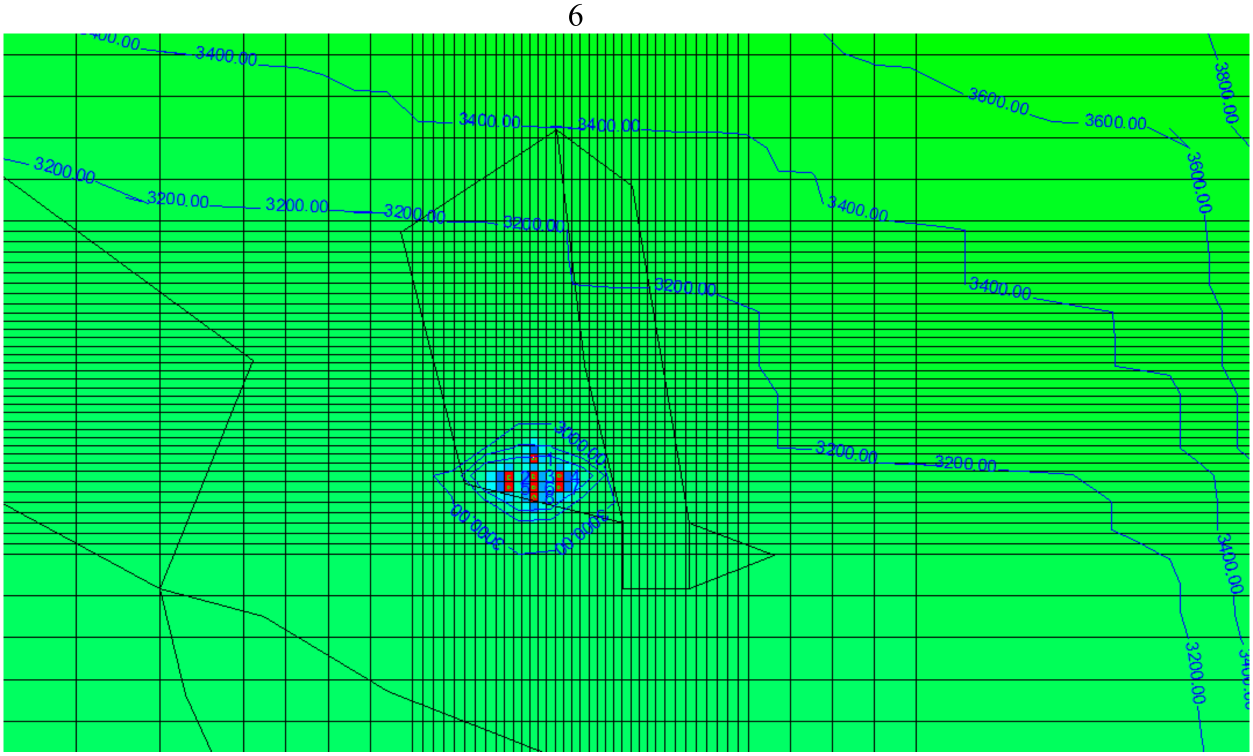

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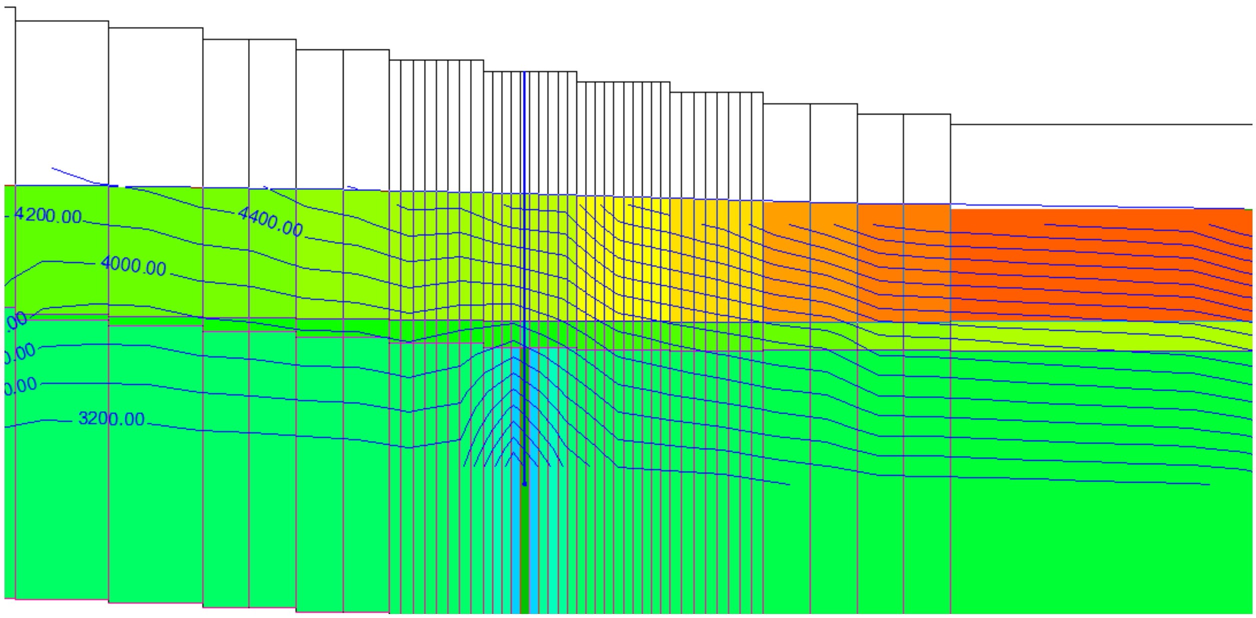

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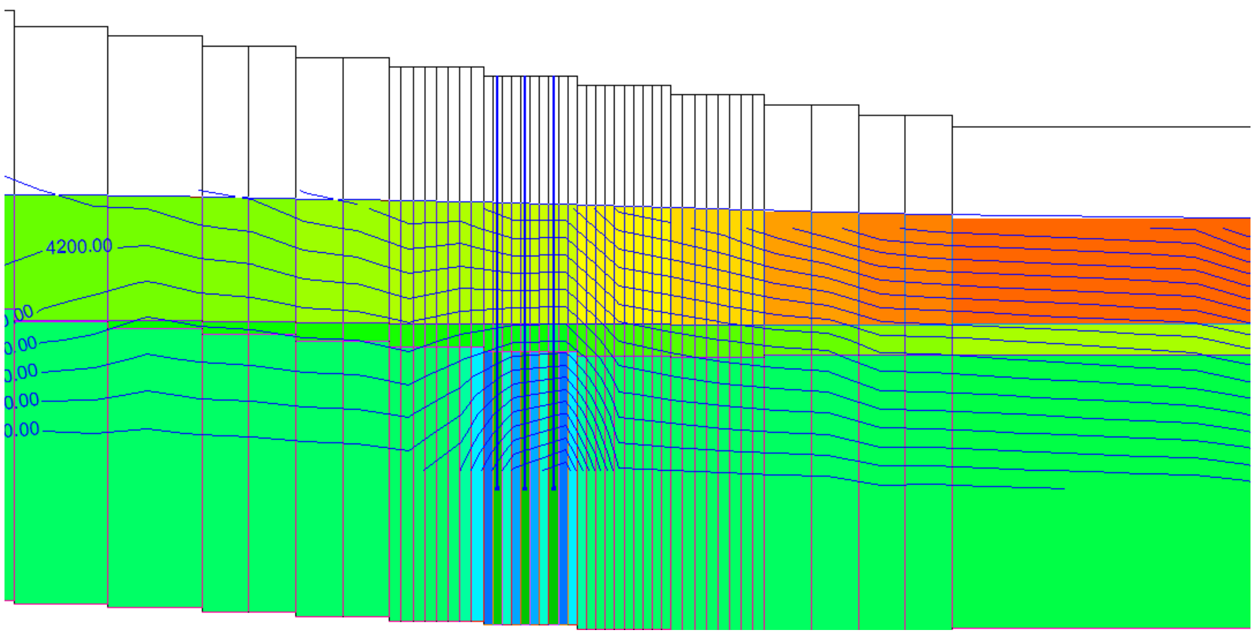

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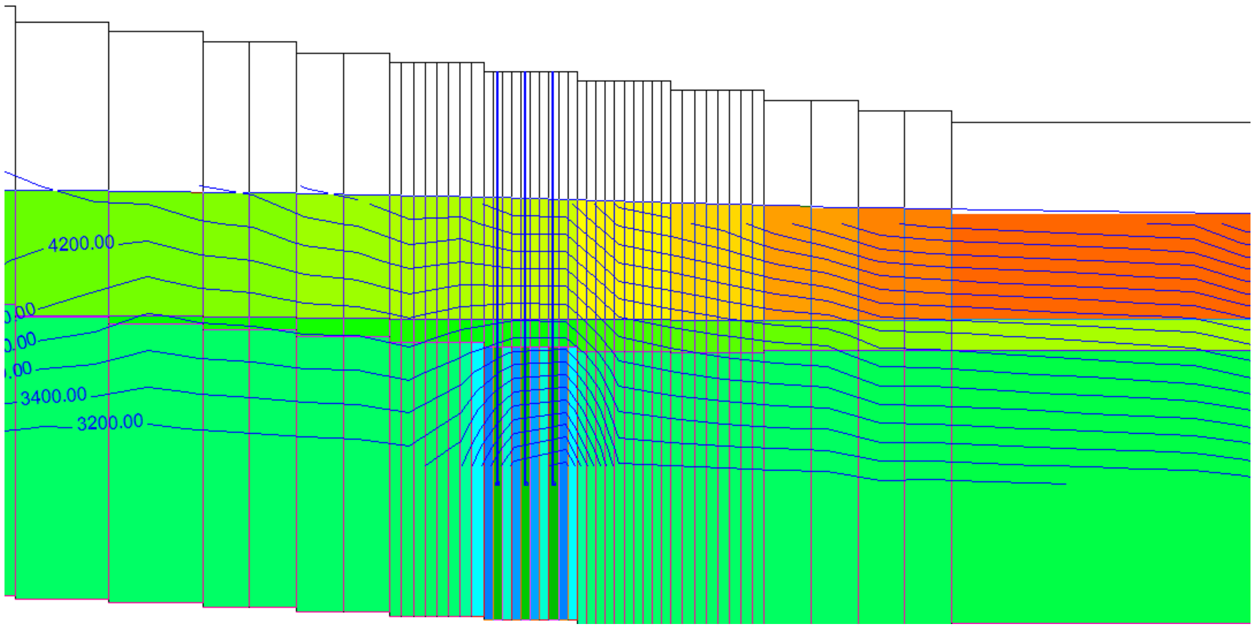

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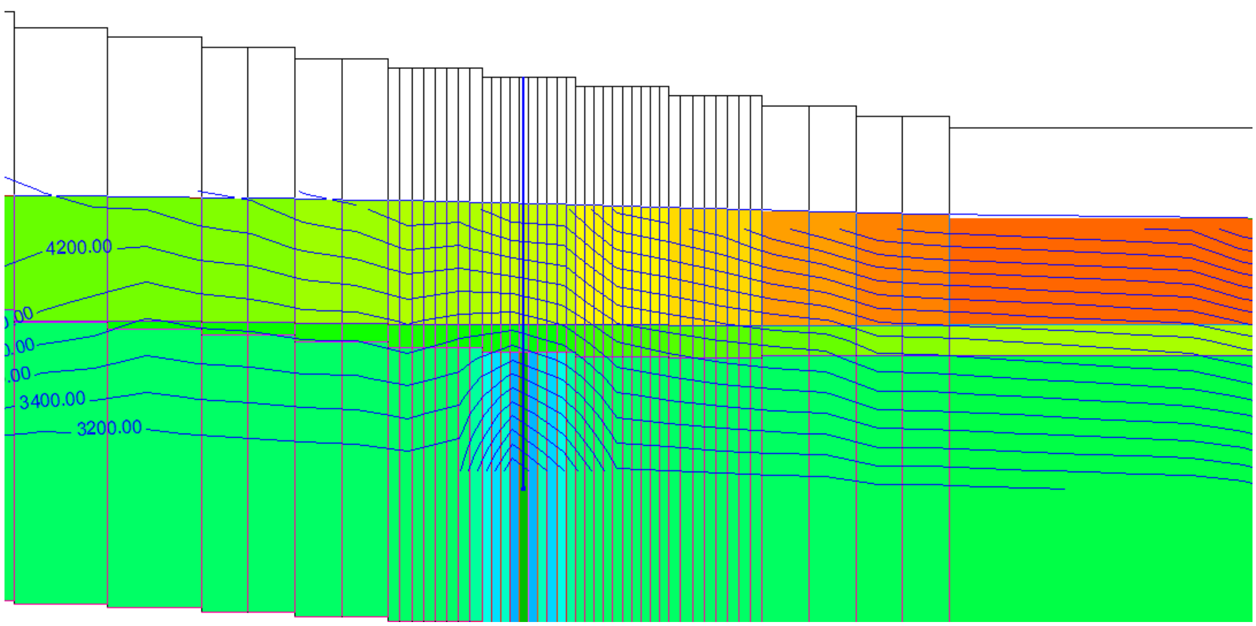

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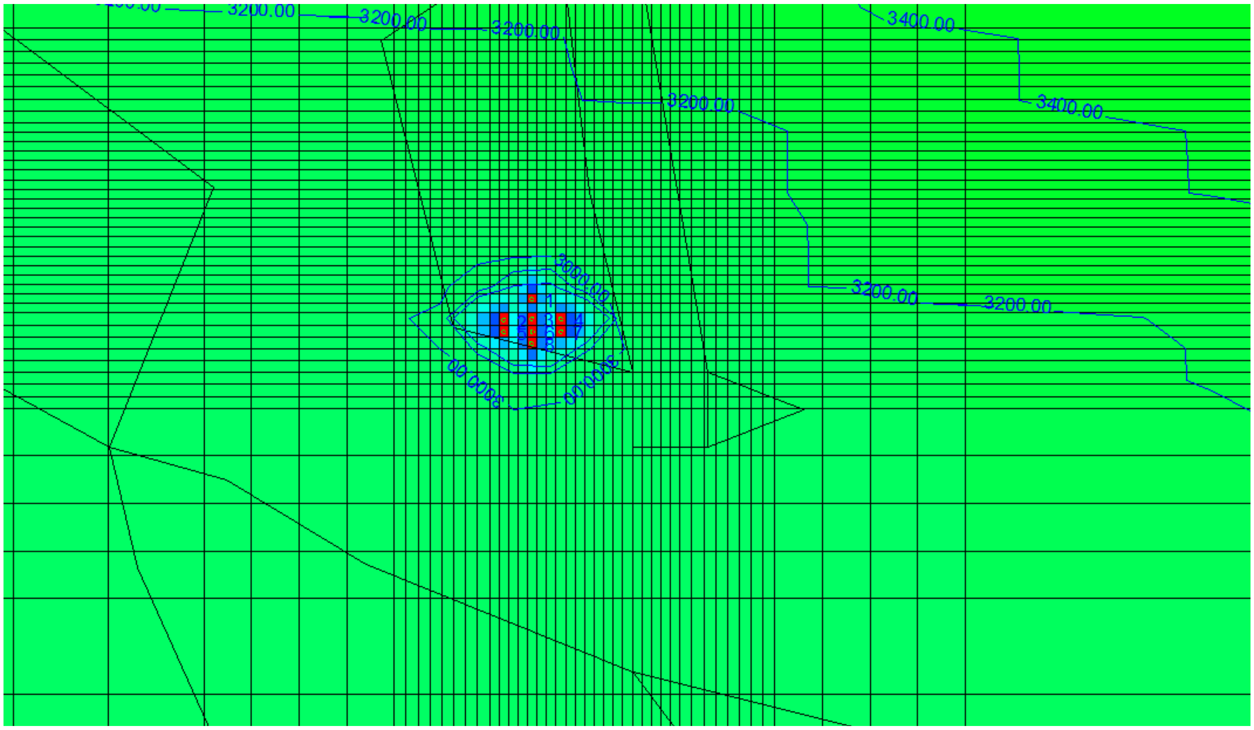

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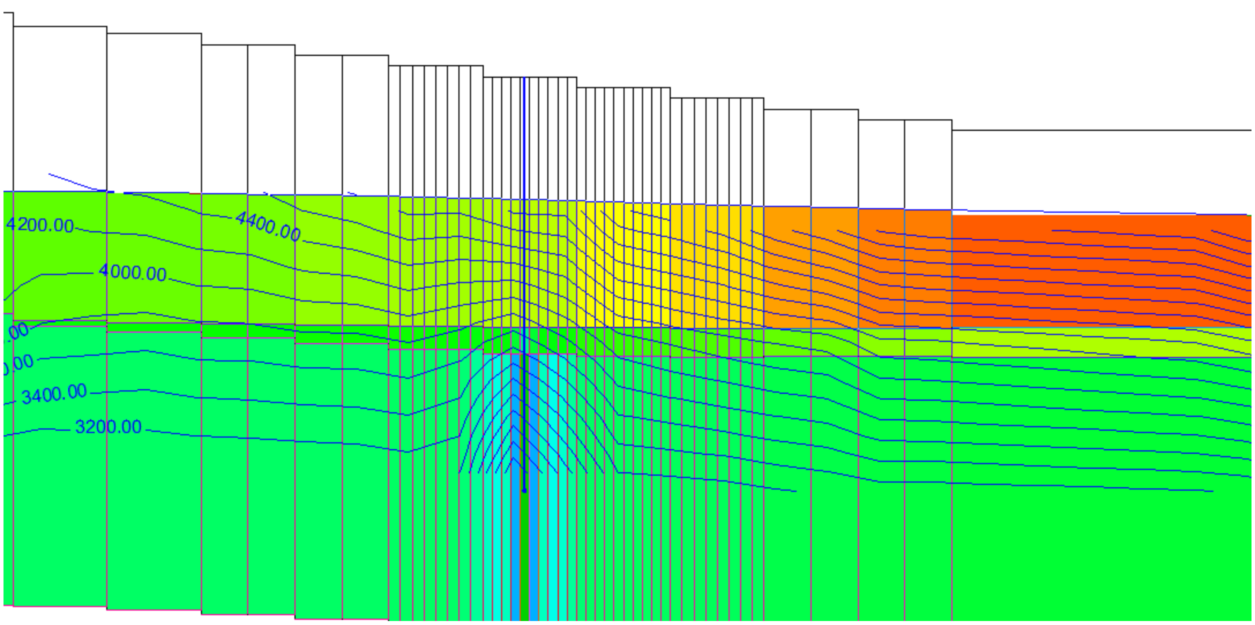

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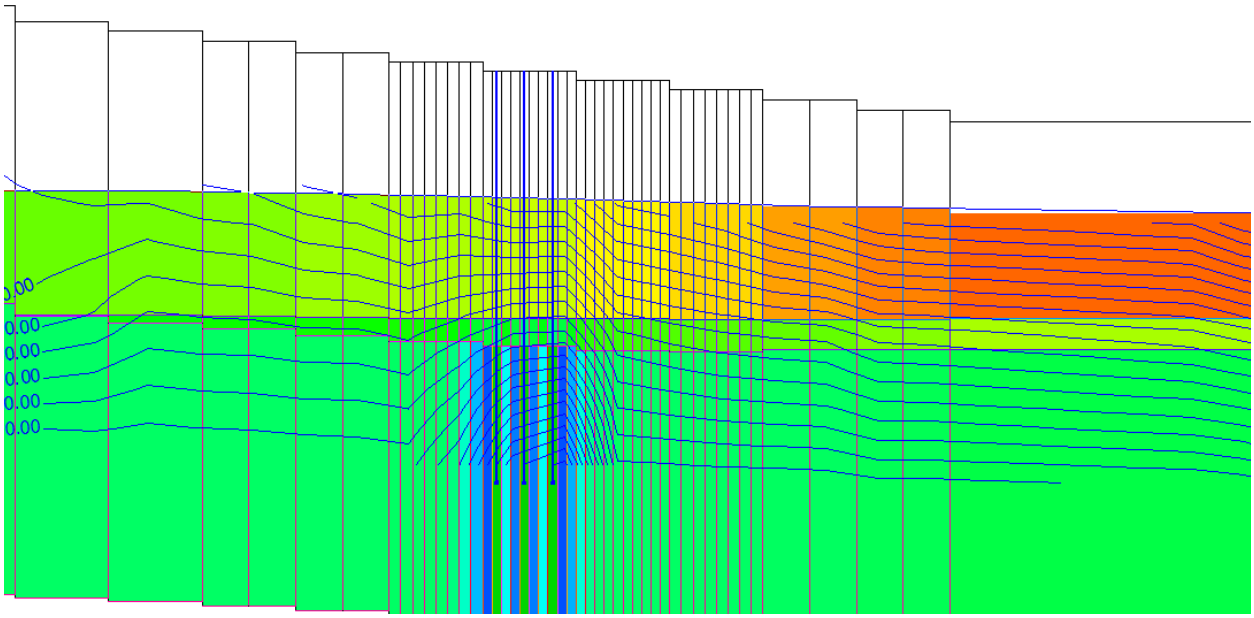

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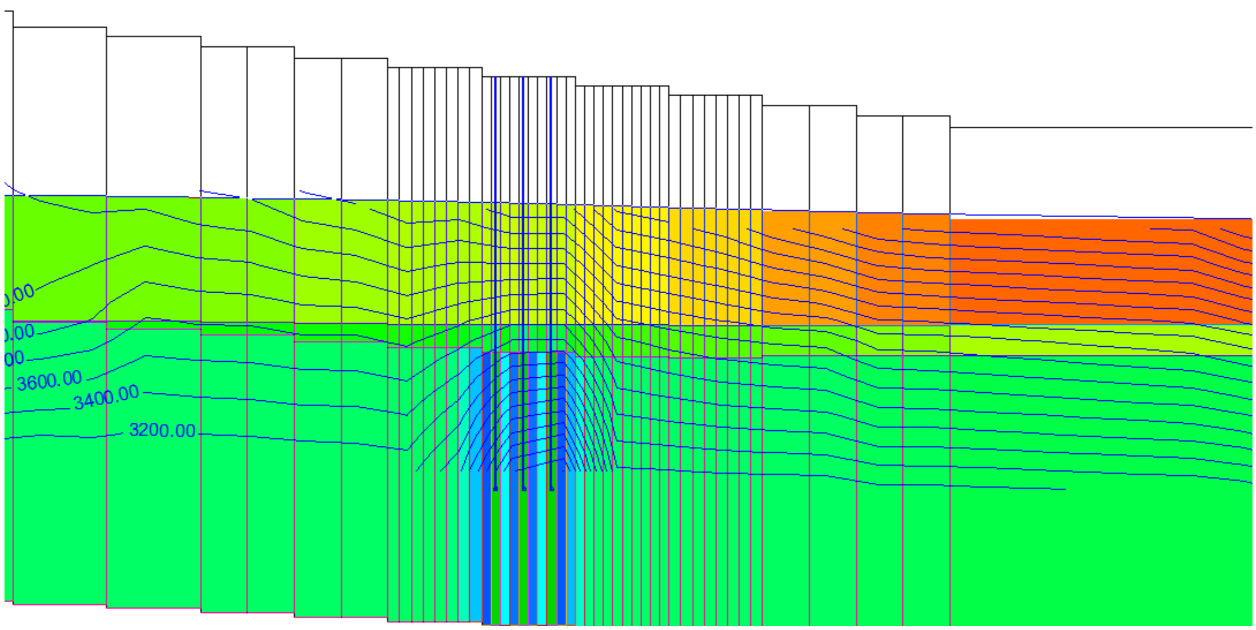

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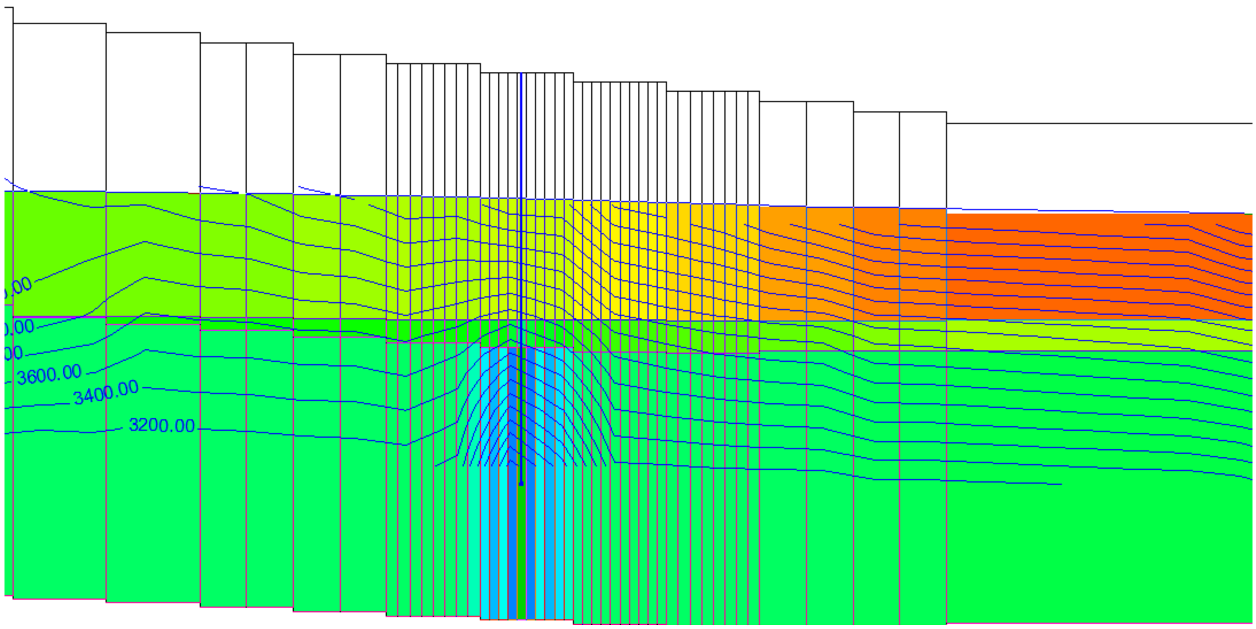

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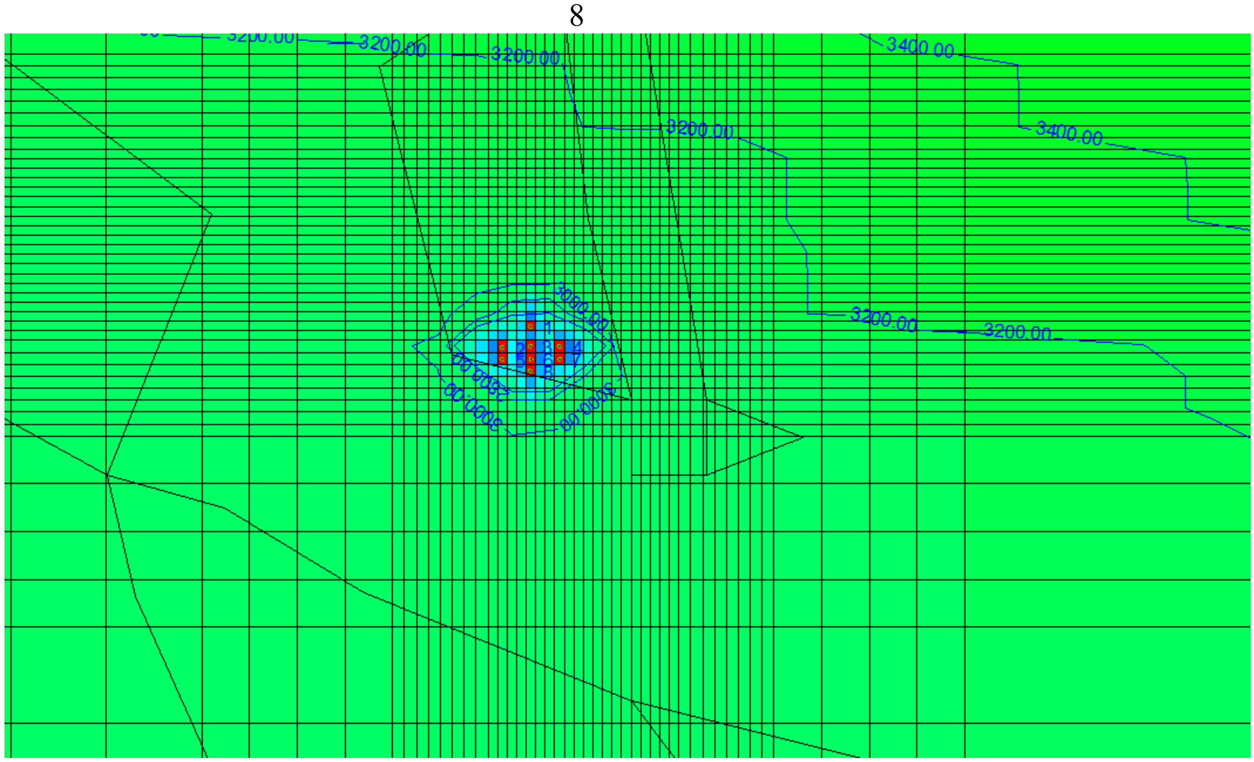

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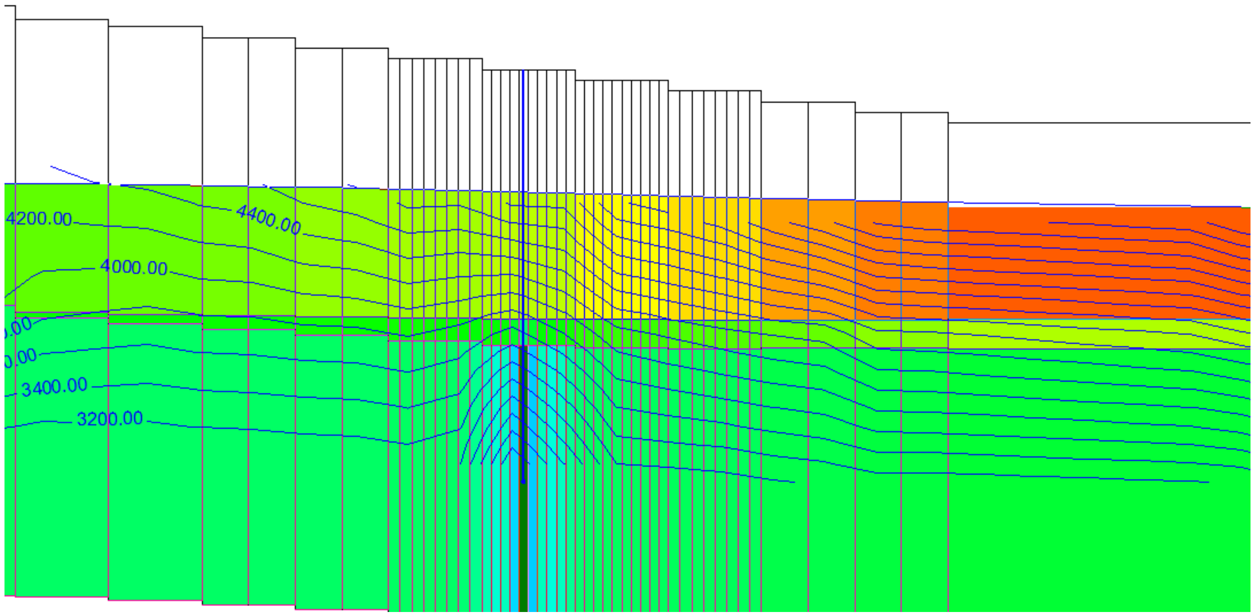

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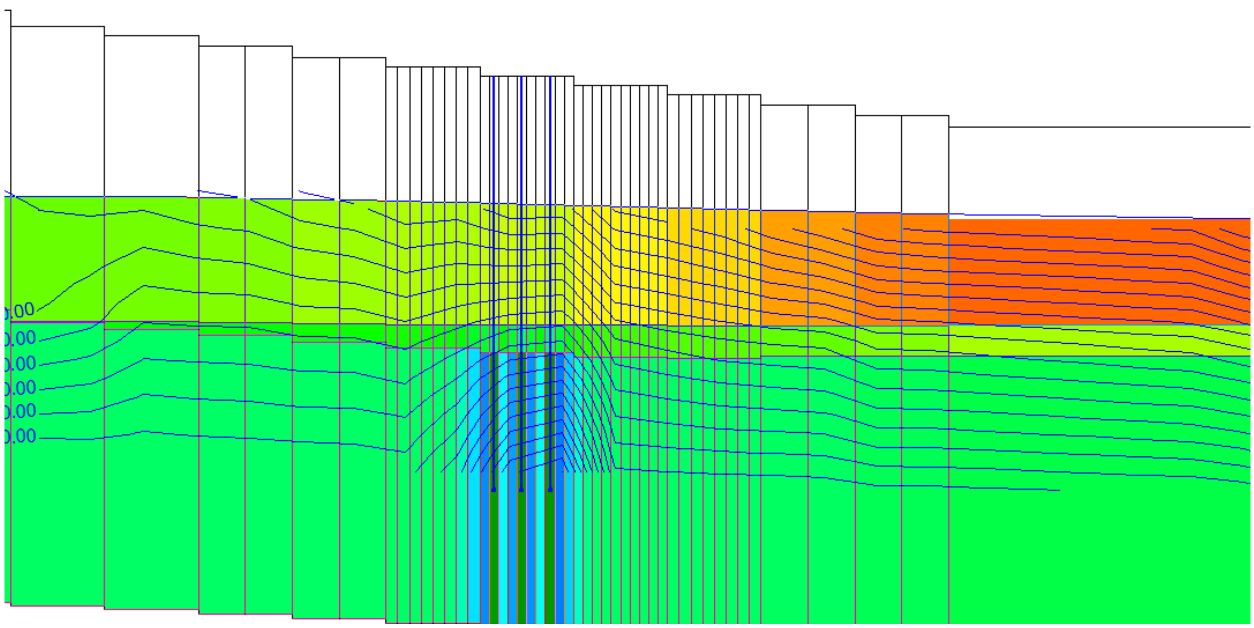

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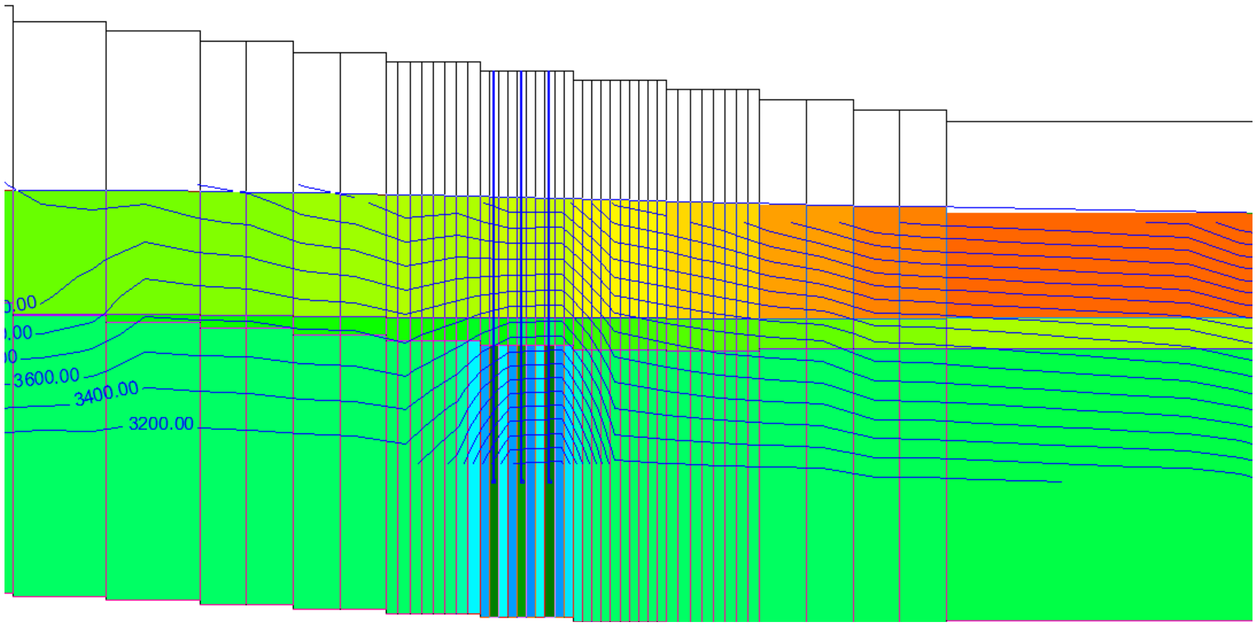

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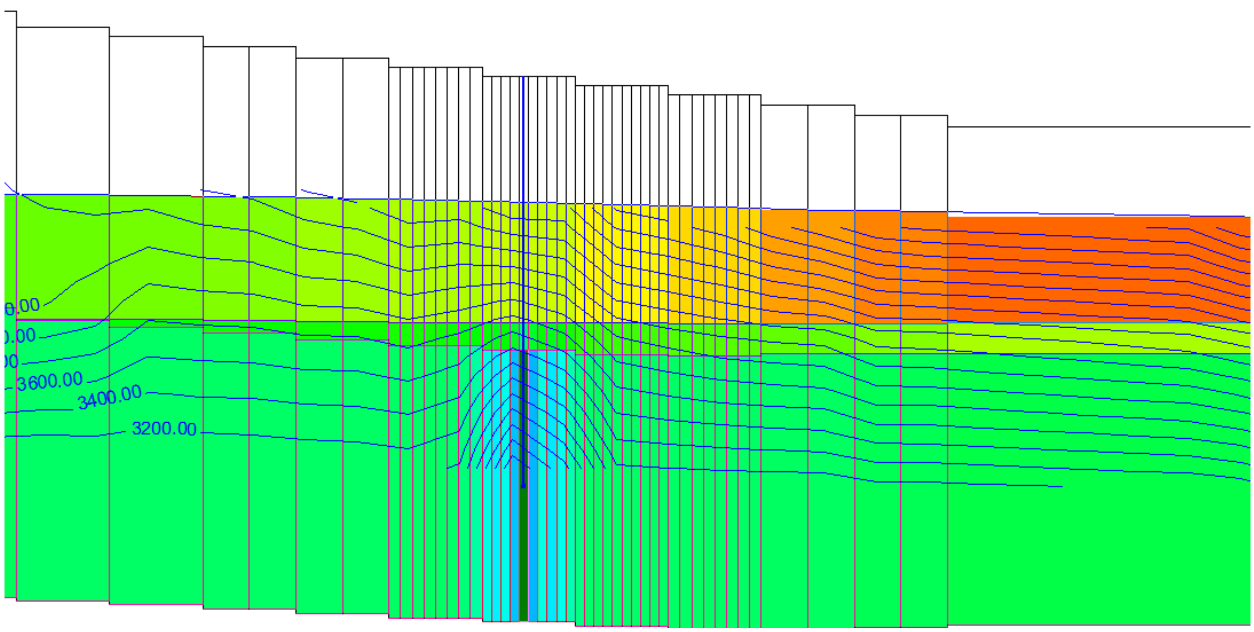

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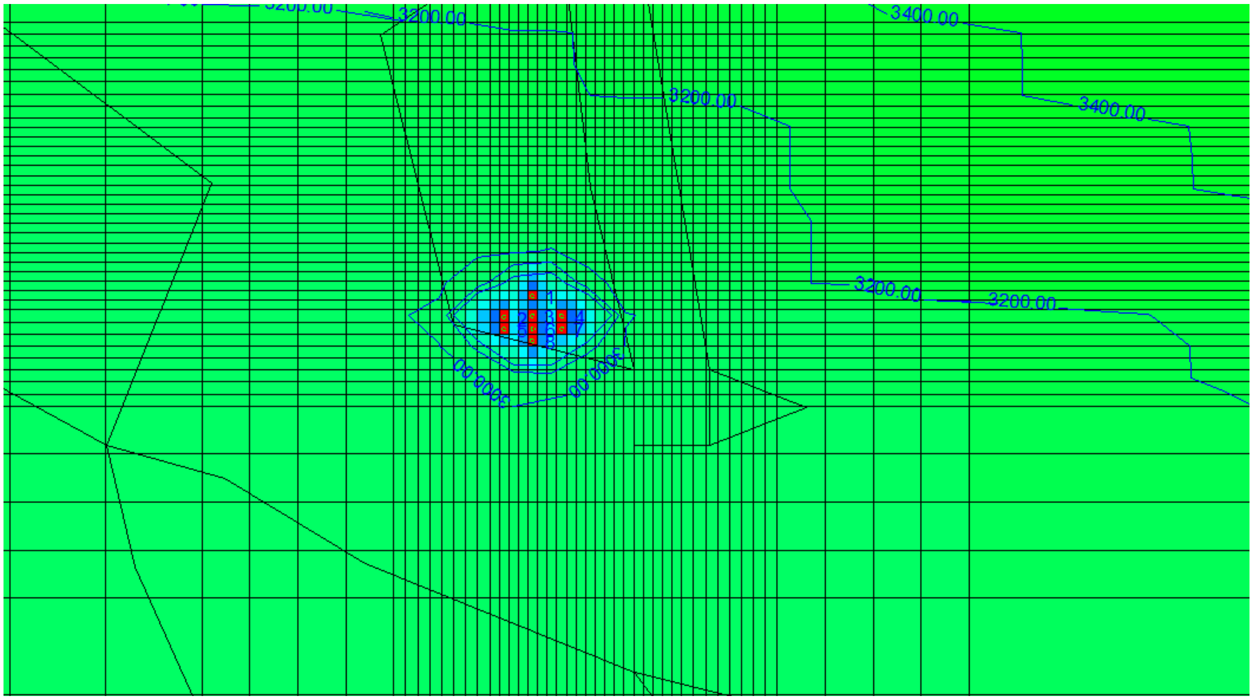

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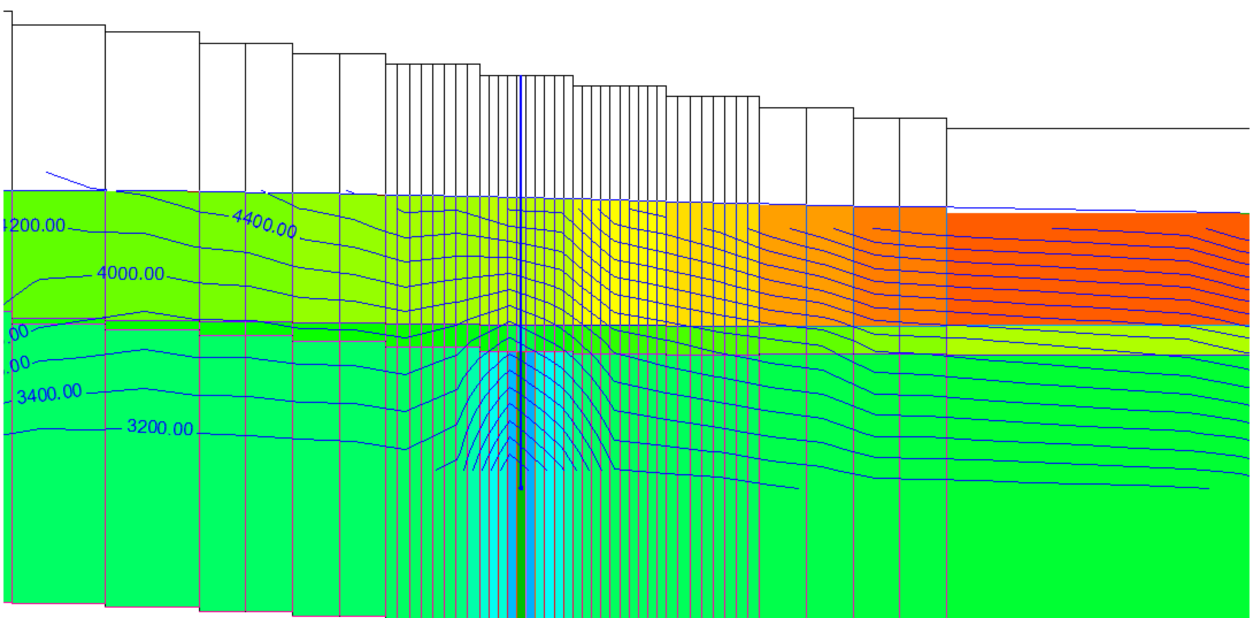

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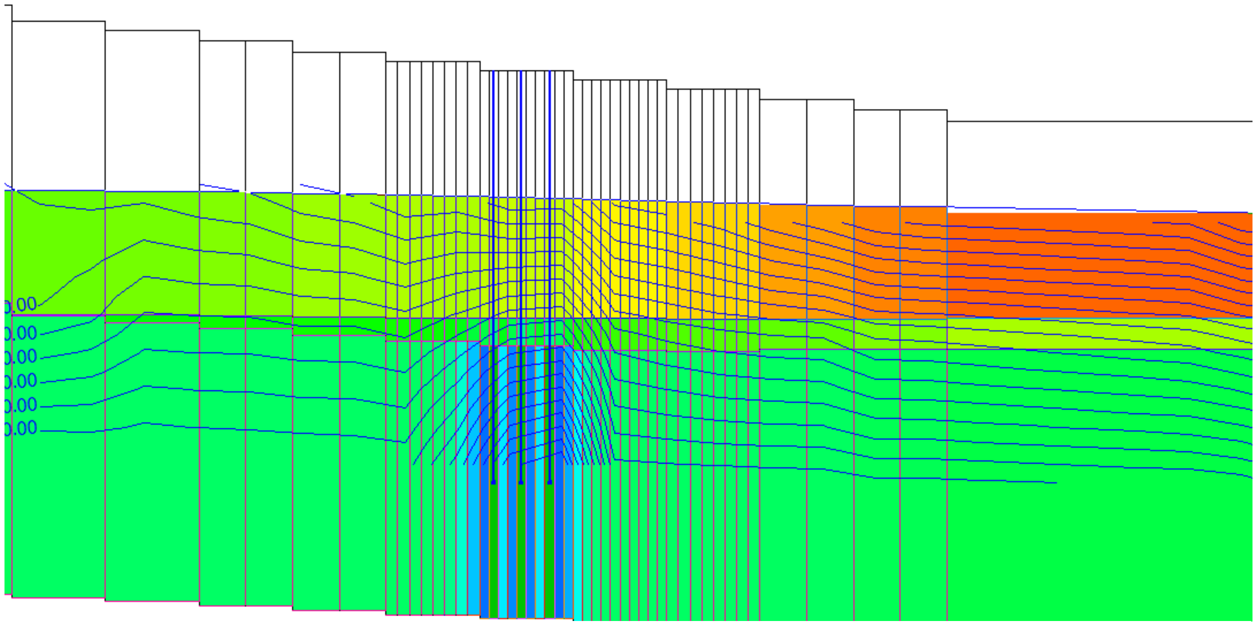

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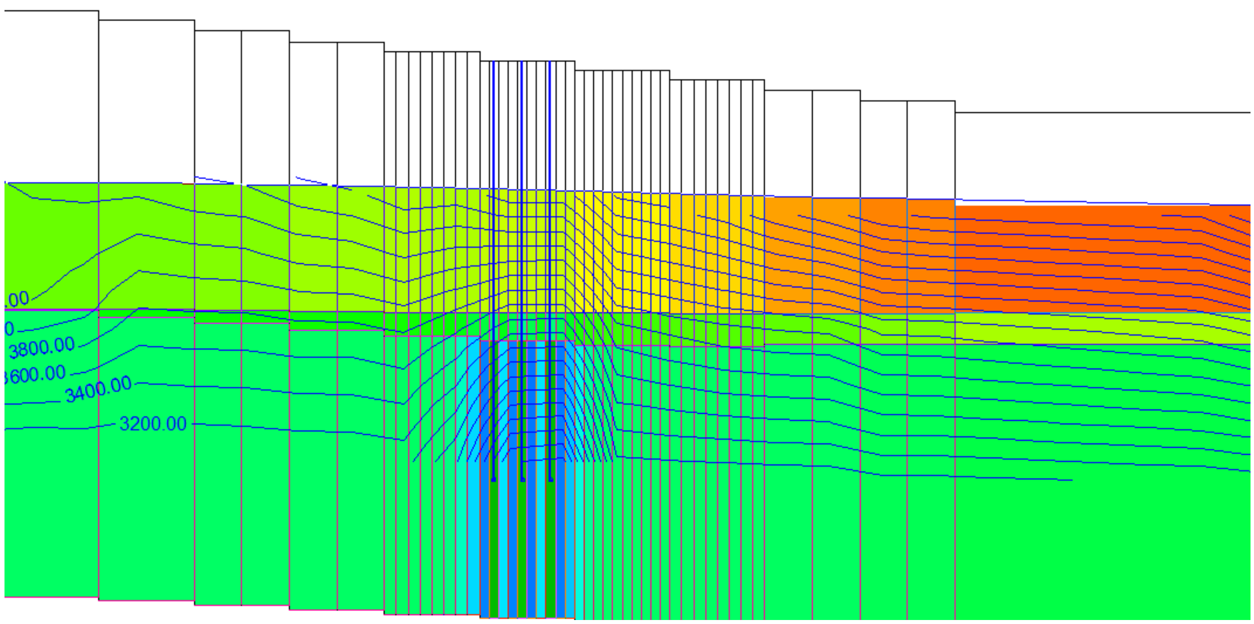

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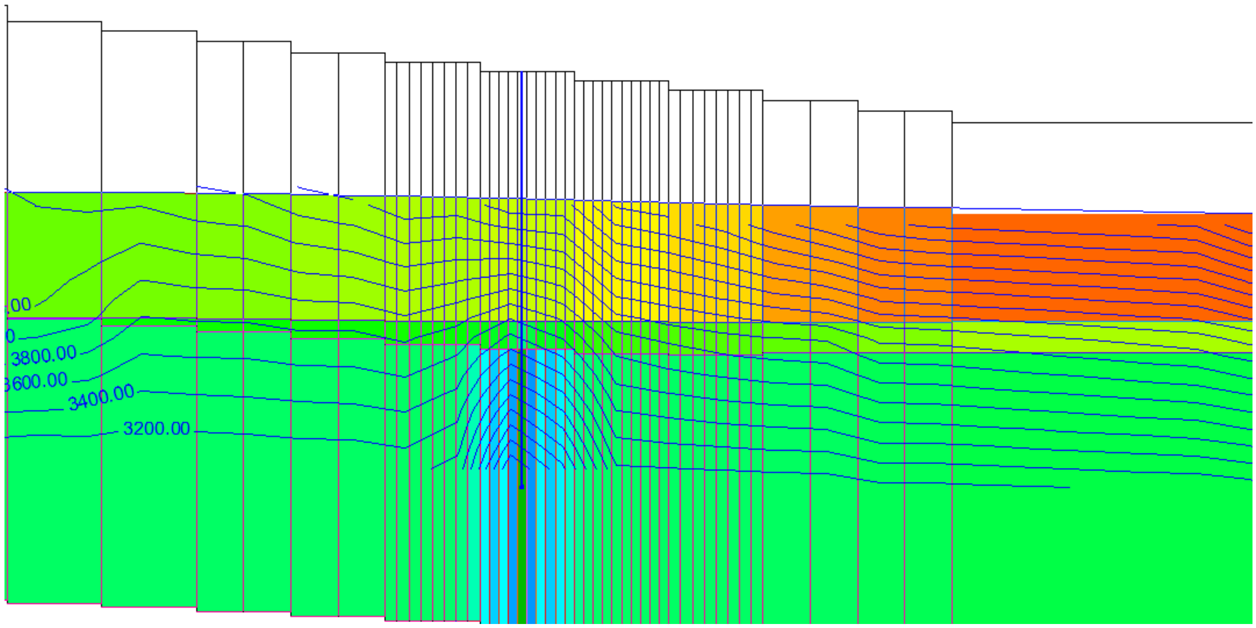

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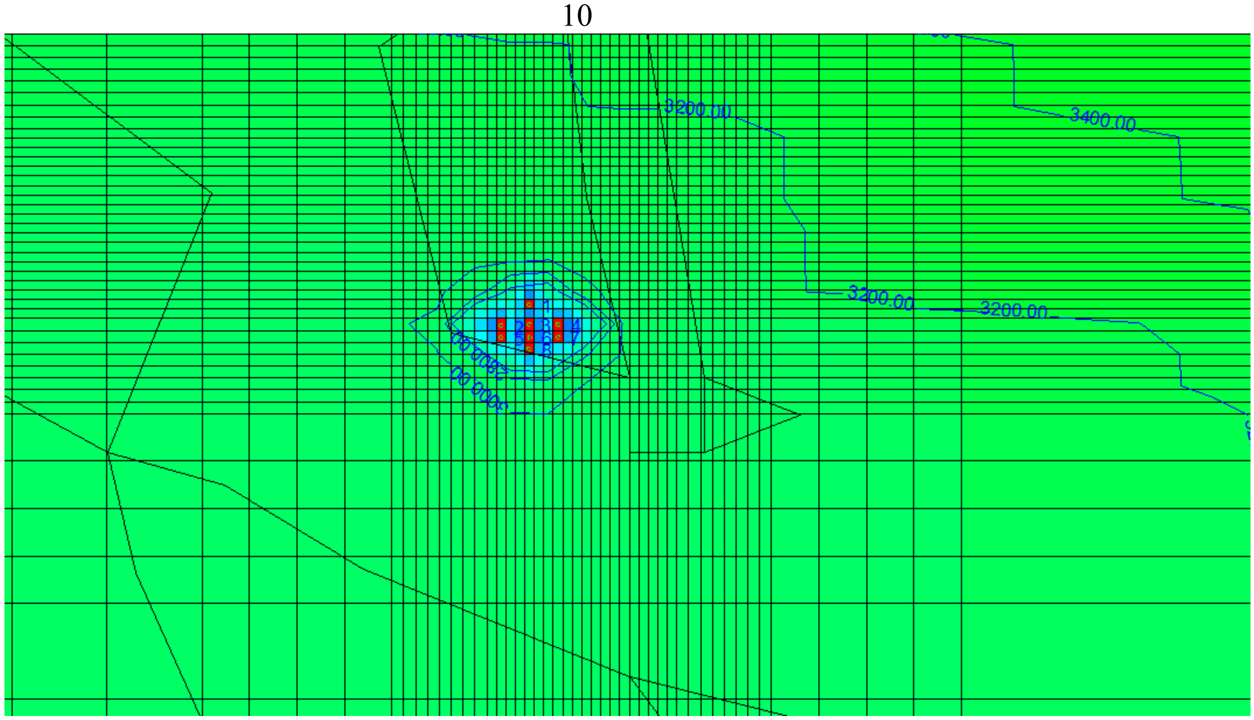

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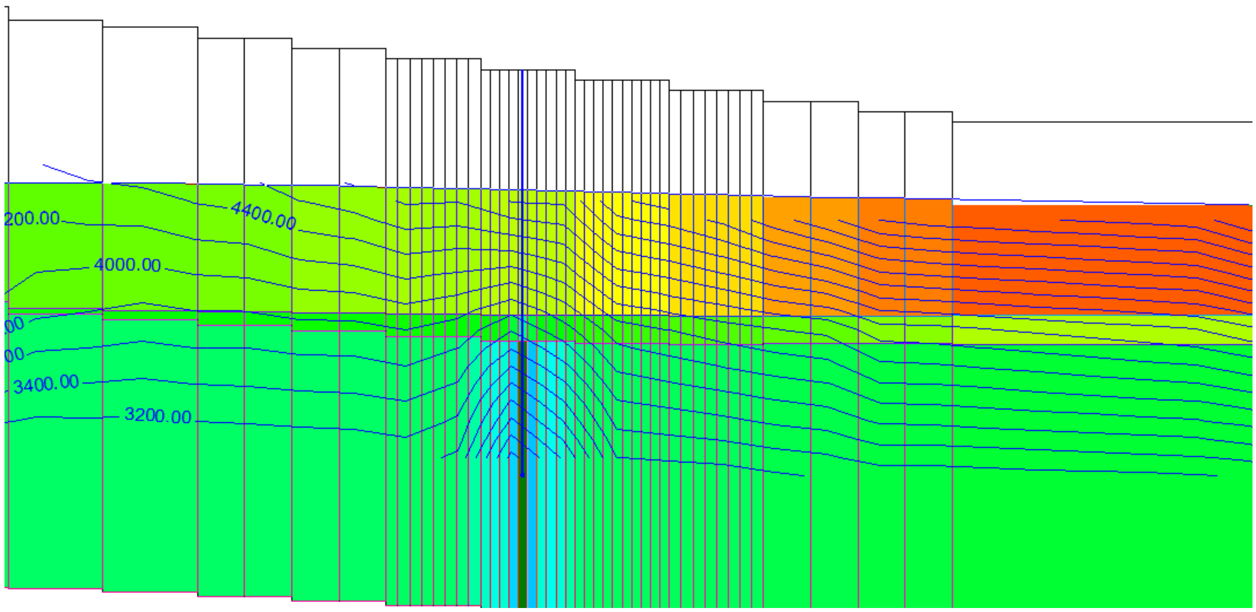

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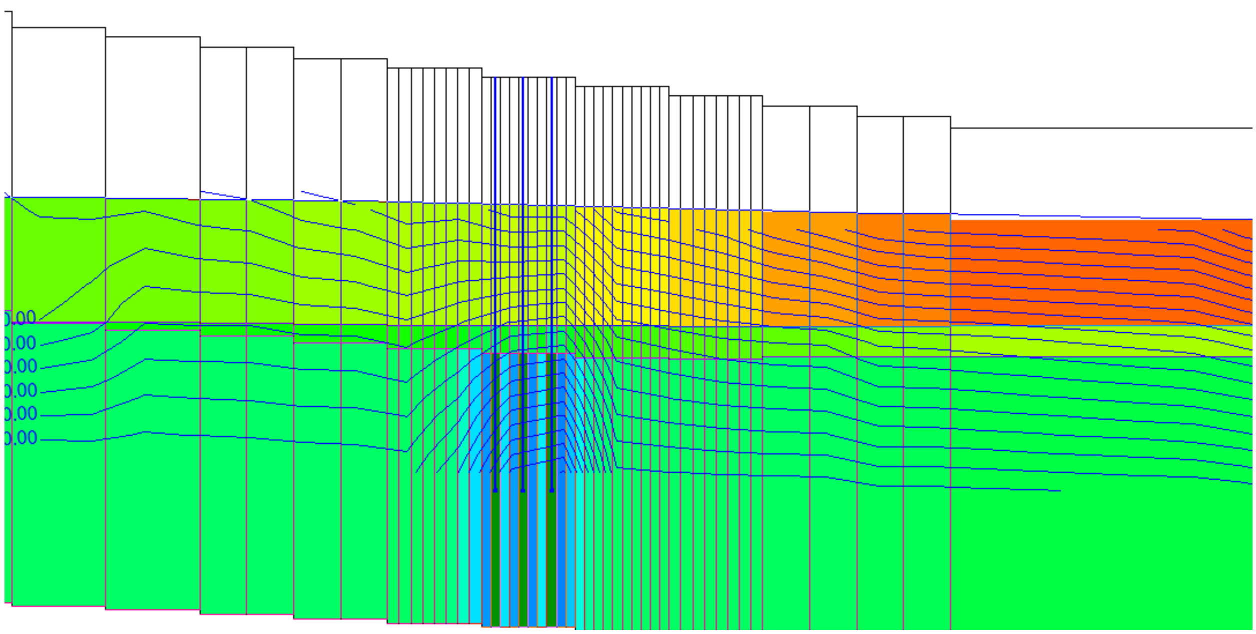

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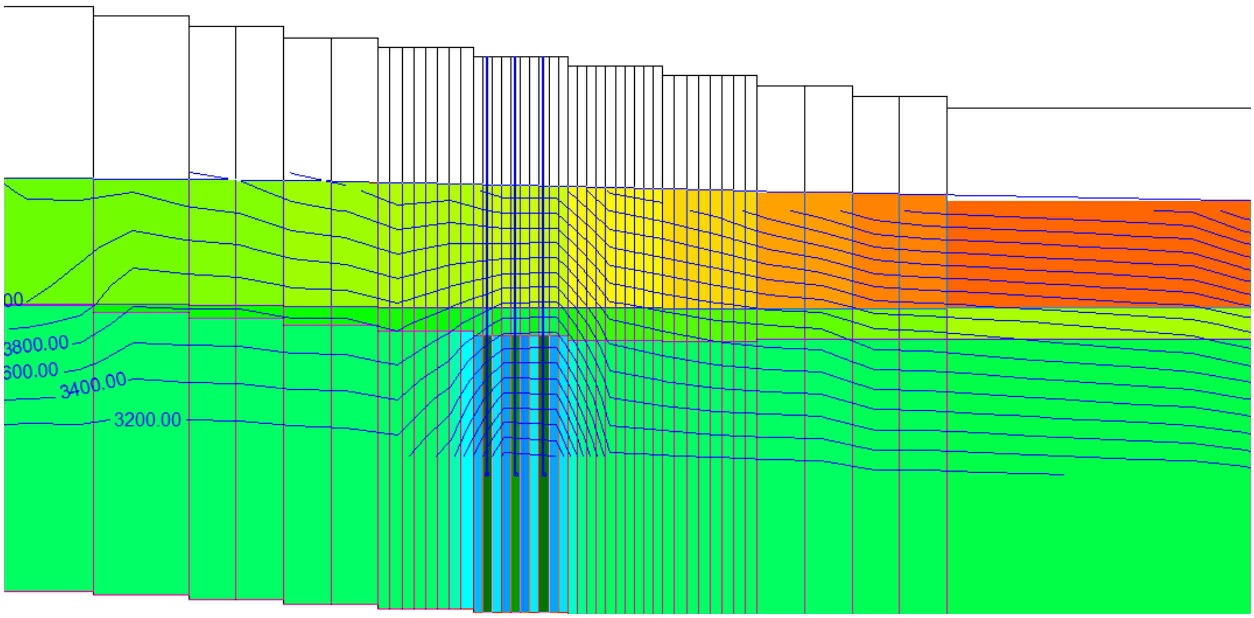

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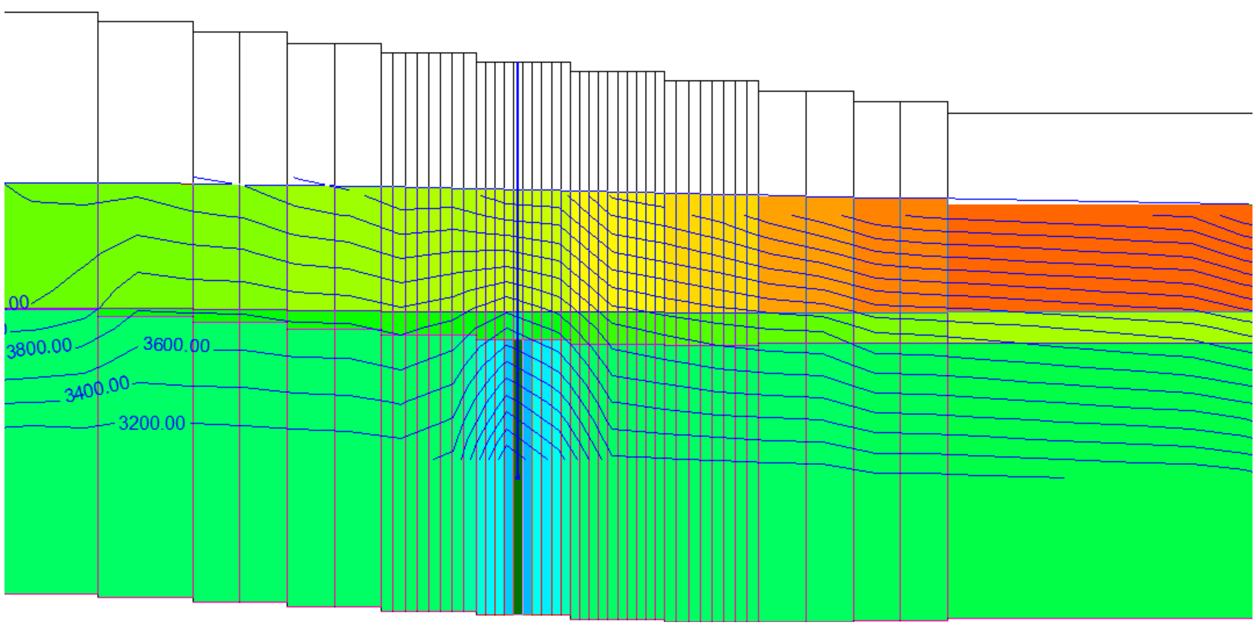

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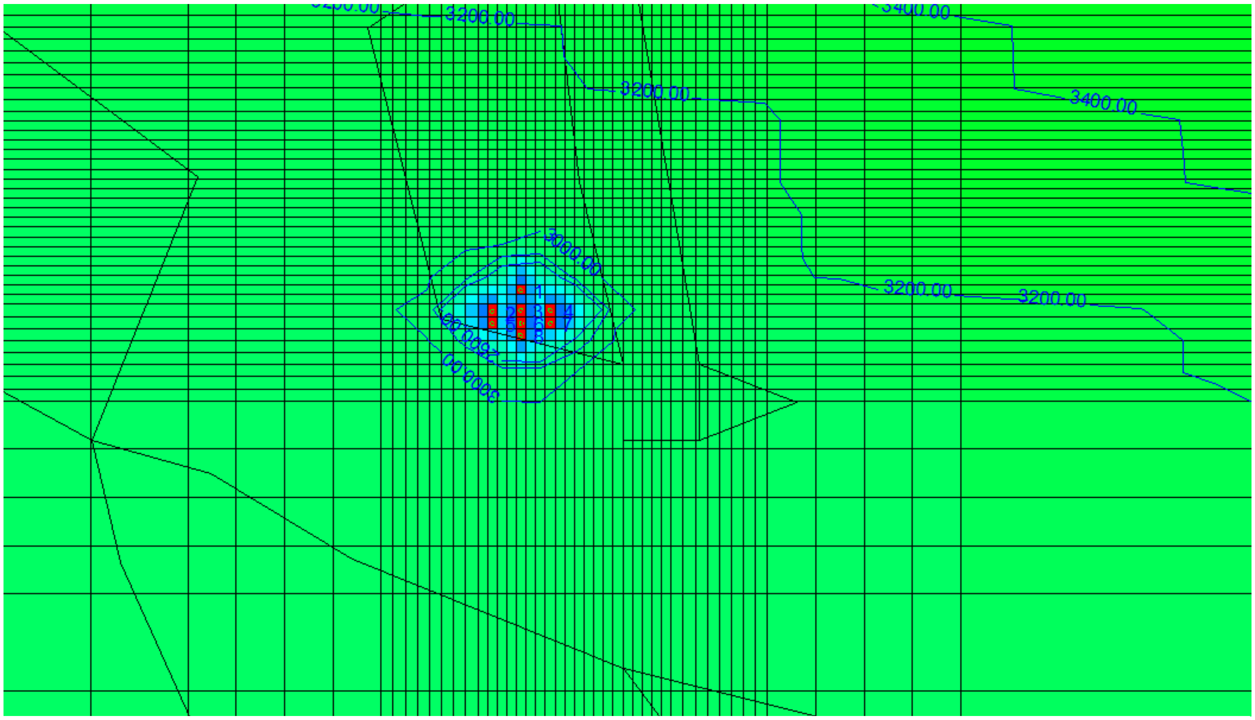

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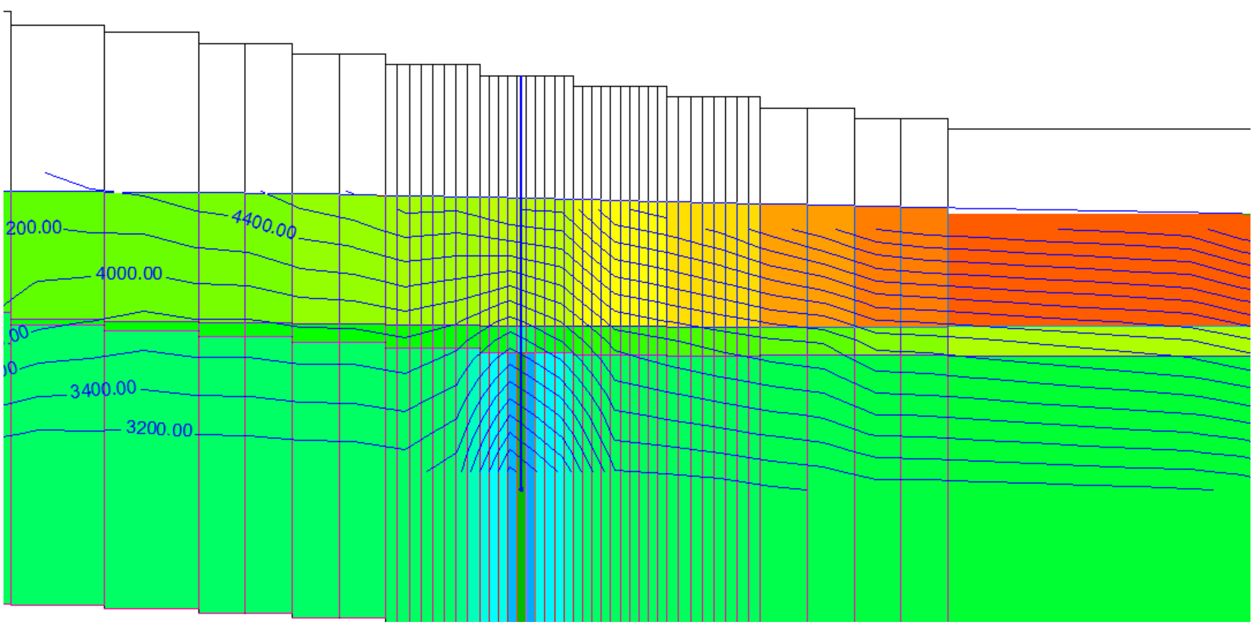

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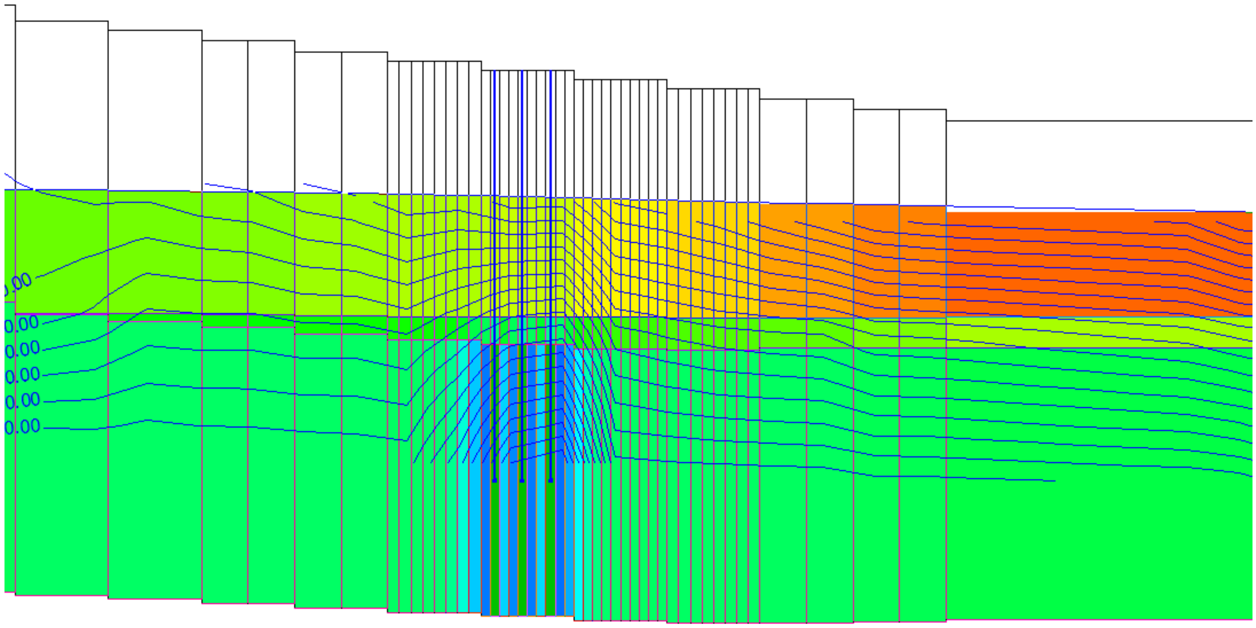

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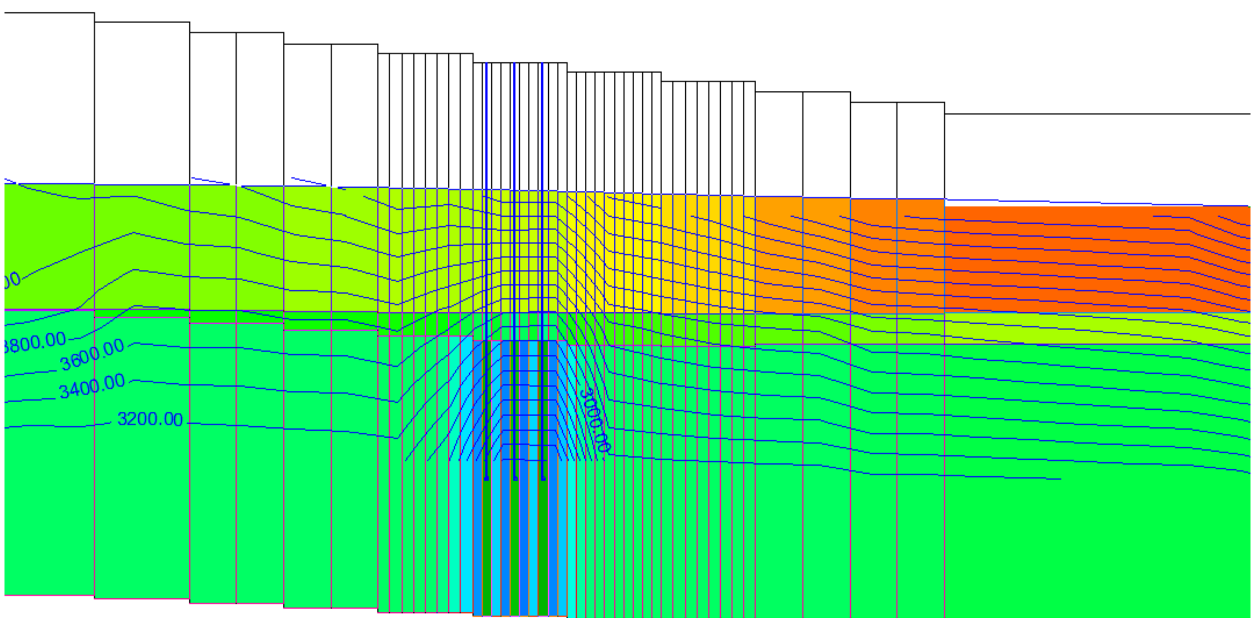

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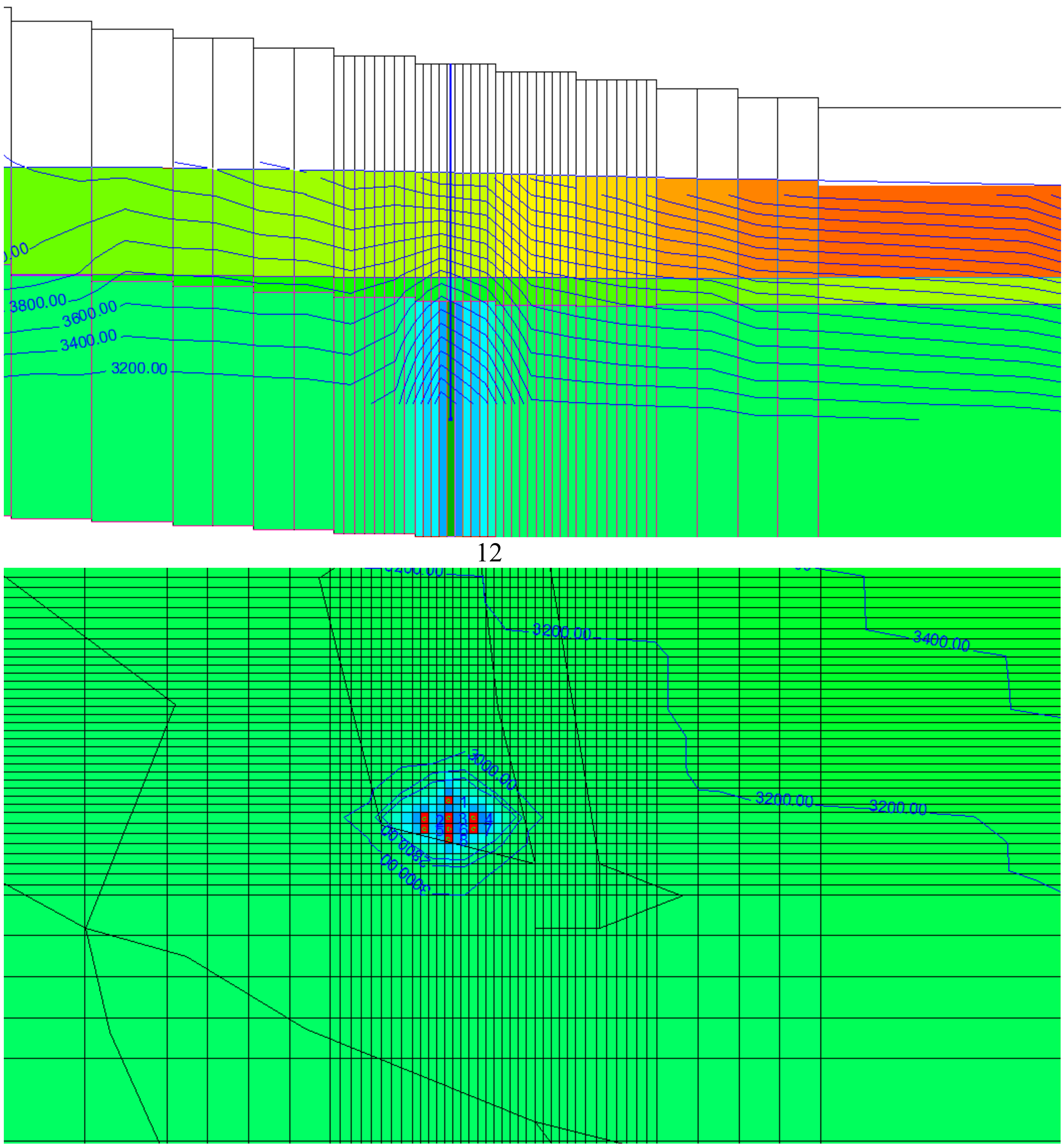

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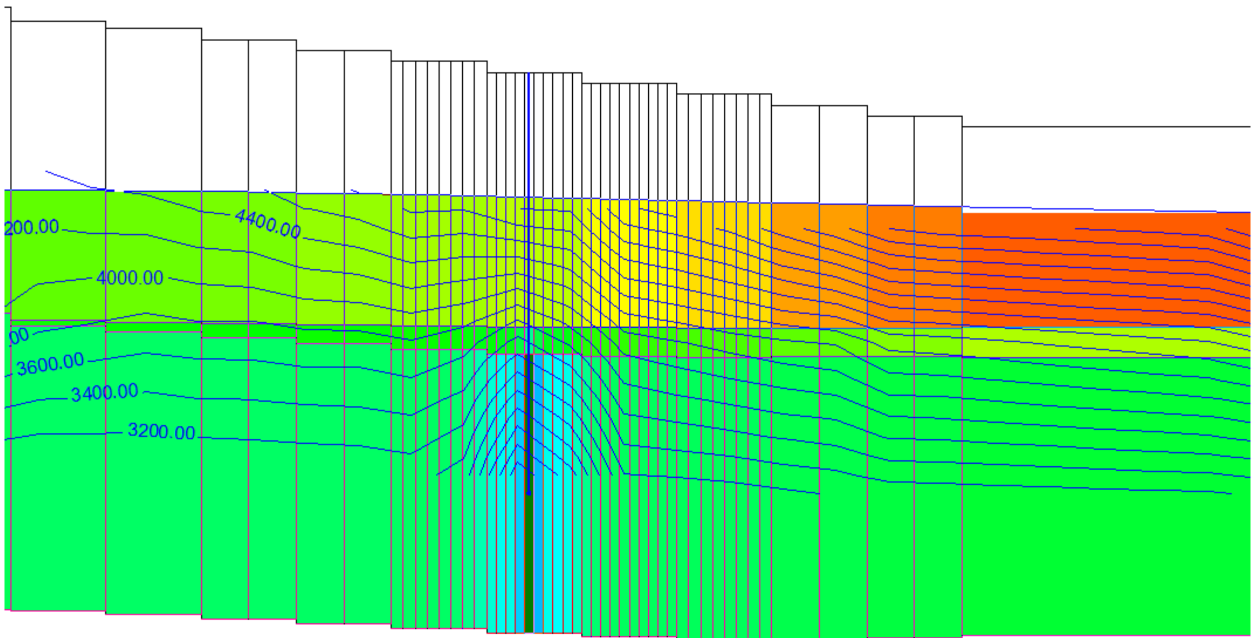

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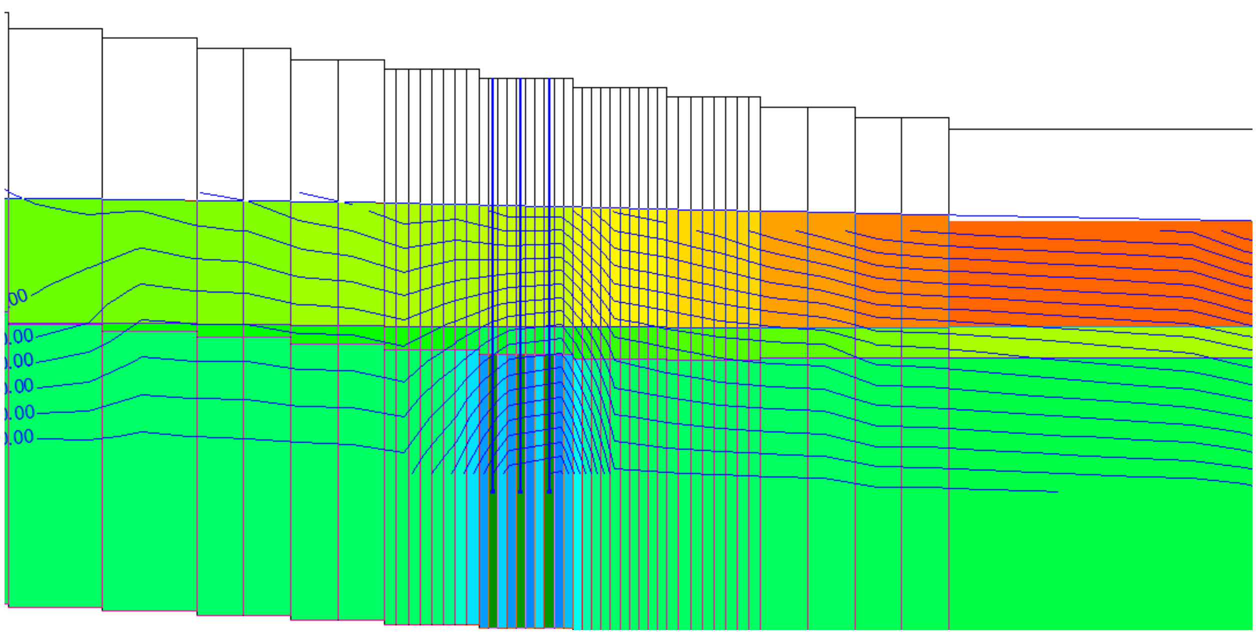

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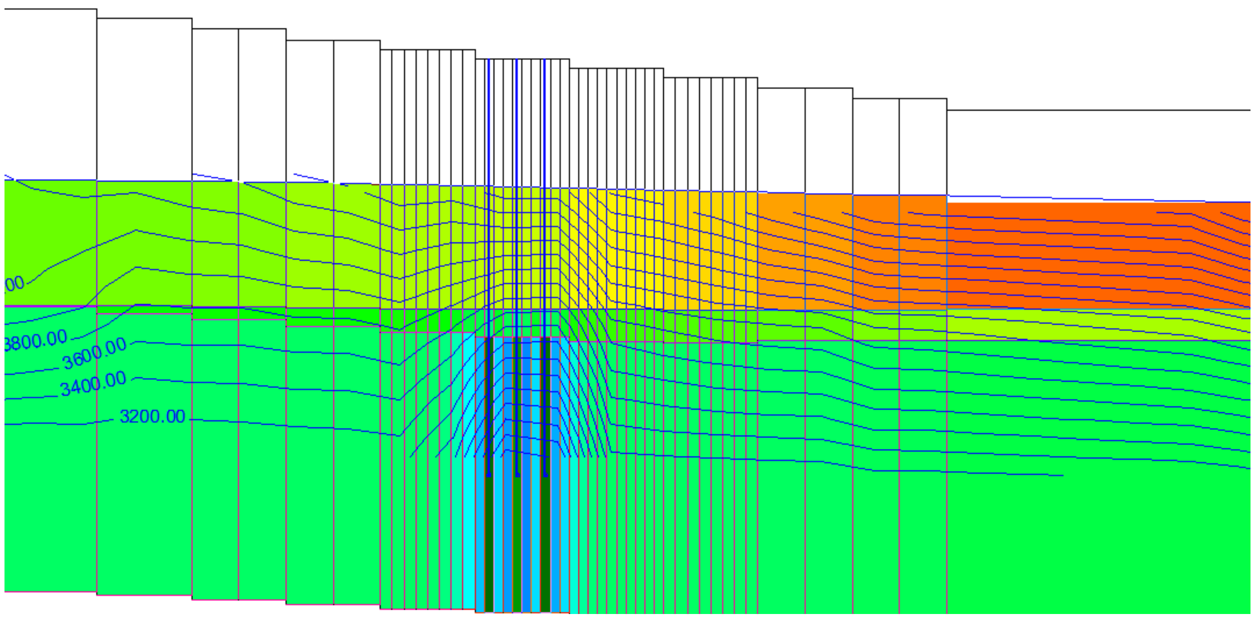

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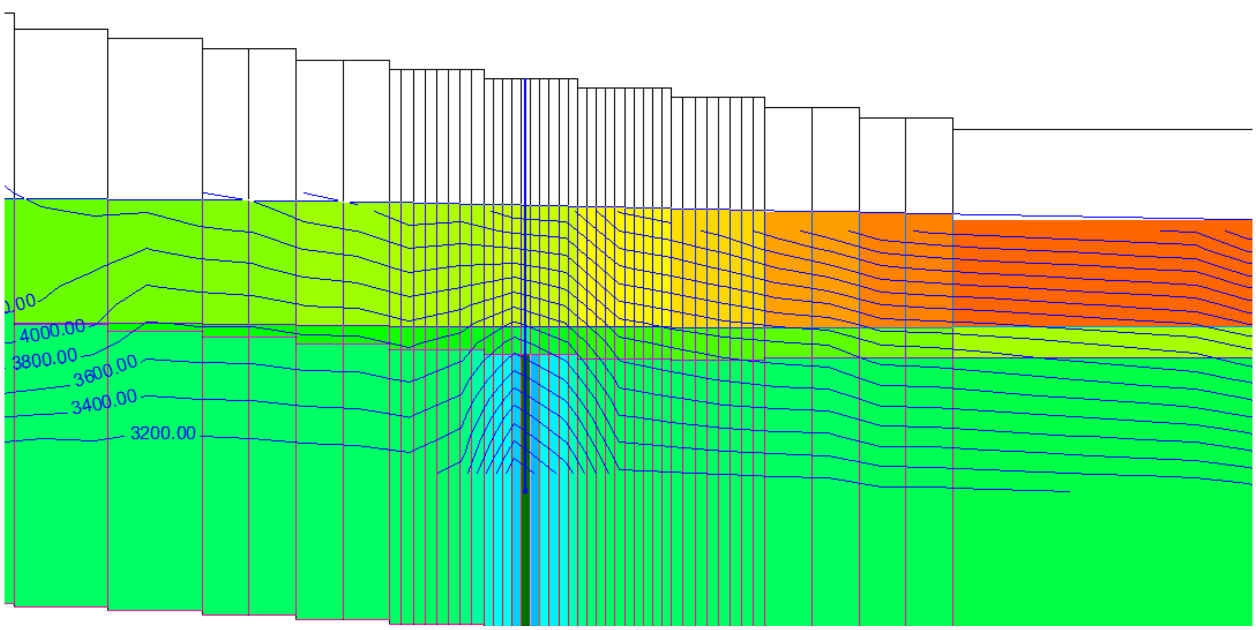
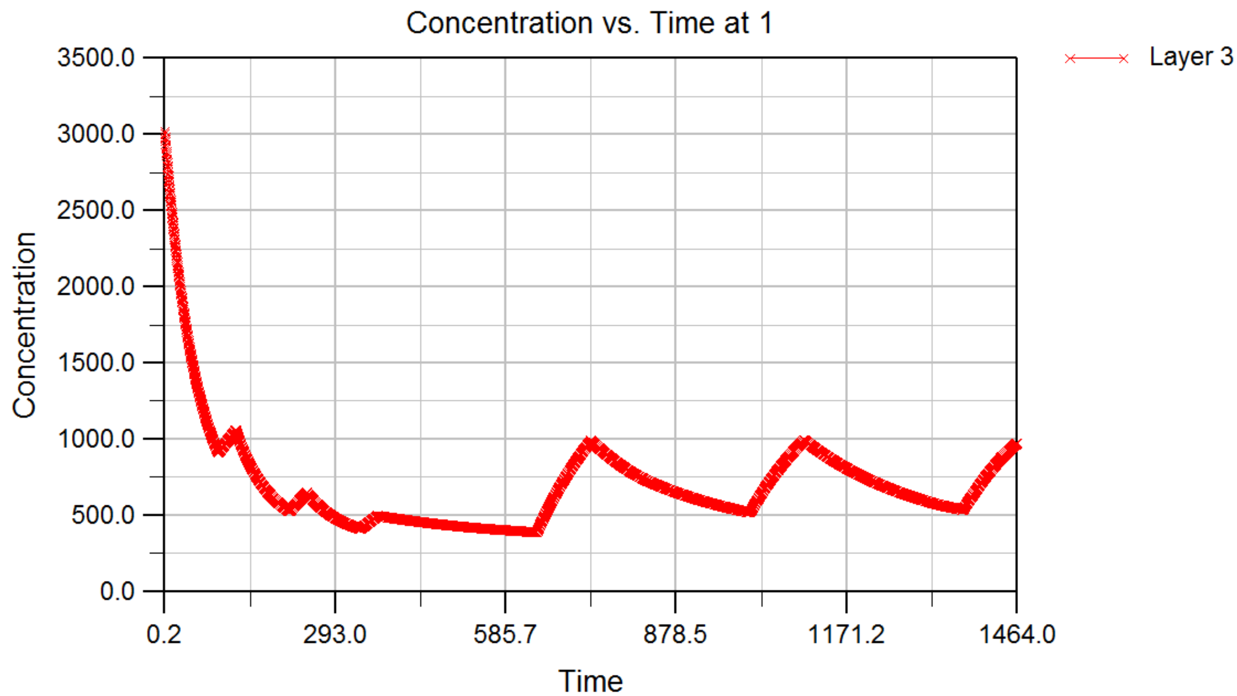
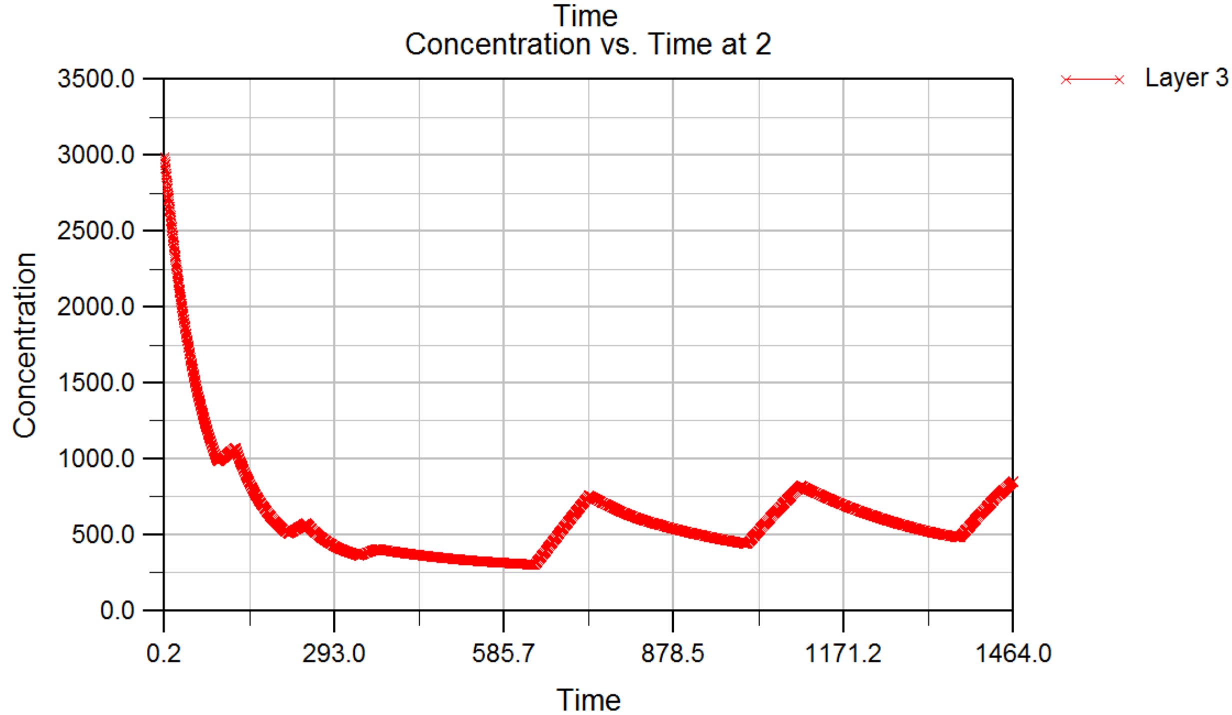
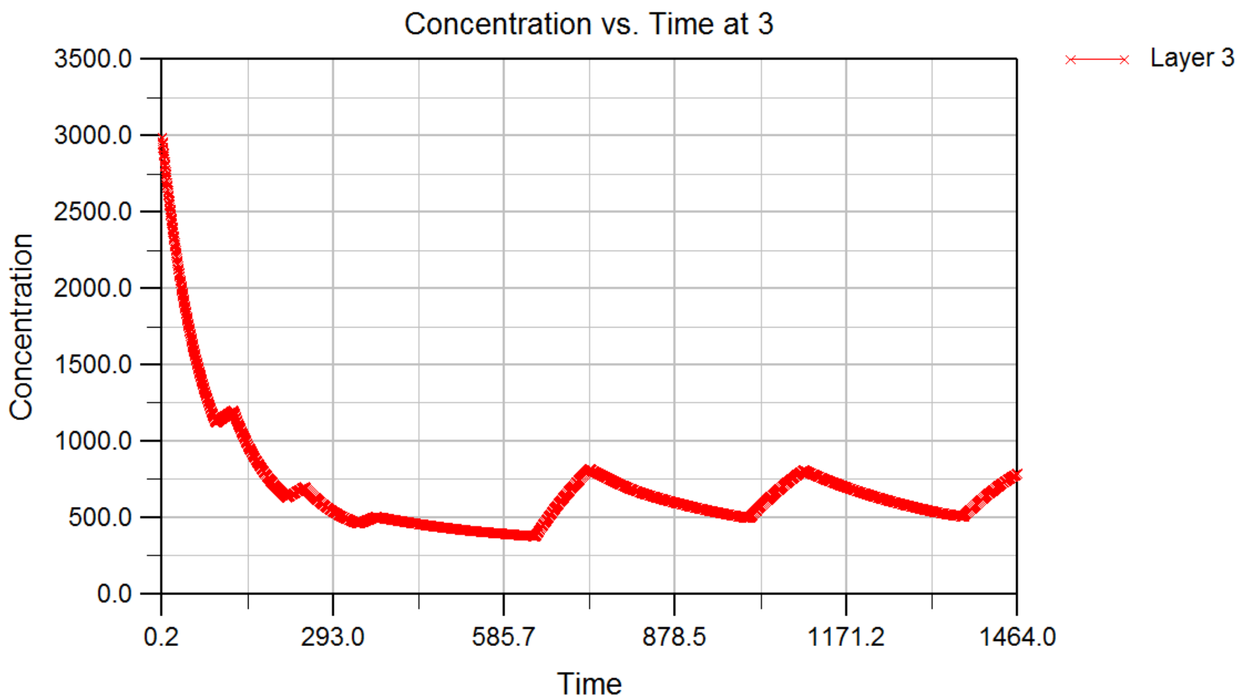



Concentration vs. Time at 1
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.2
293.0
585.7
878.5
1171.2
1464.0
Time


Concentration vs. Time at 2
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.2
293.0
585.7
878.5
1171.2
1464.0
Time


Concentration vs. Time at 3
Layer 3
Concentration
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3000.0
2500.0
2000.0
1500.0
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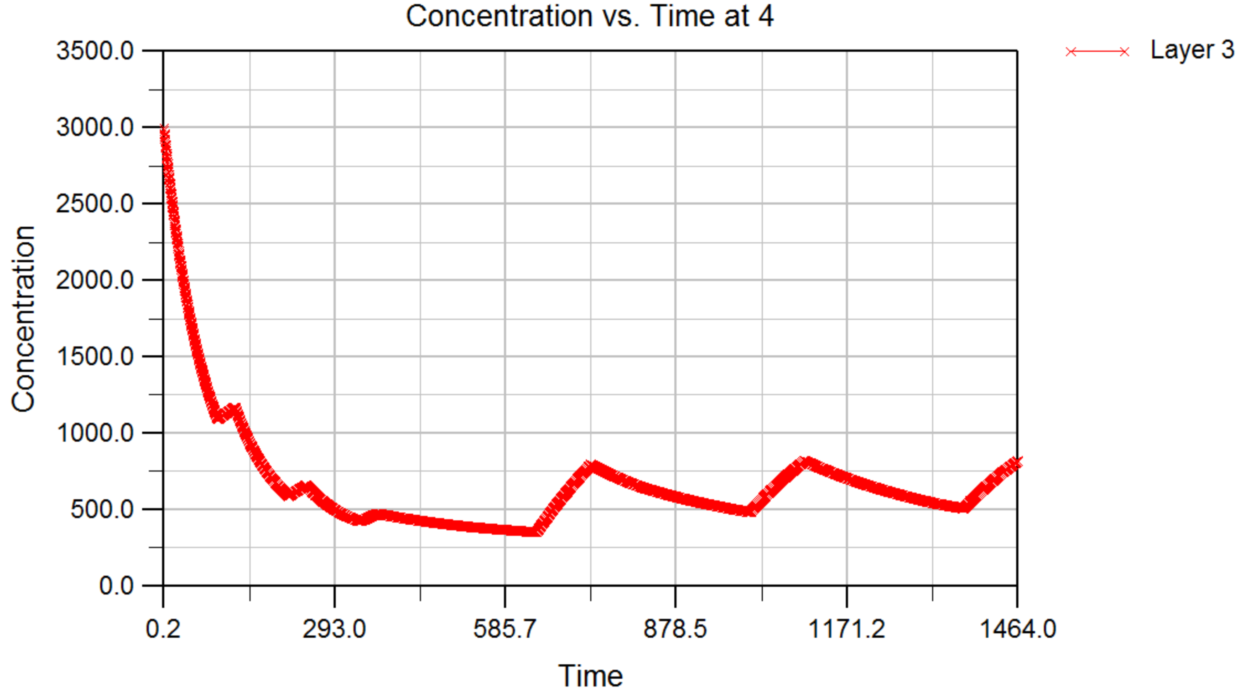
500.0
0.0
0.2
293.0
585.7
878.5
1171.2
1464.0
Time


Concentration vs. Time at 4
Layer 3
Concentration
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2500.0
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1500.0
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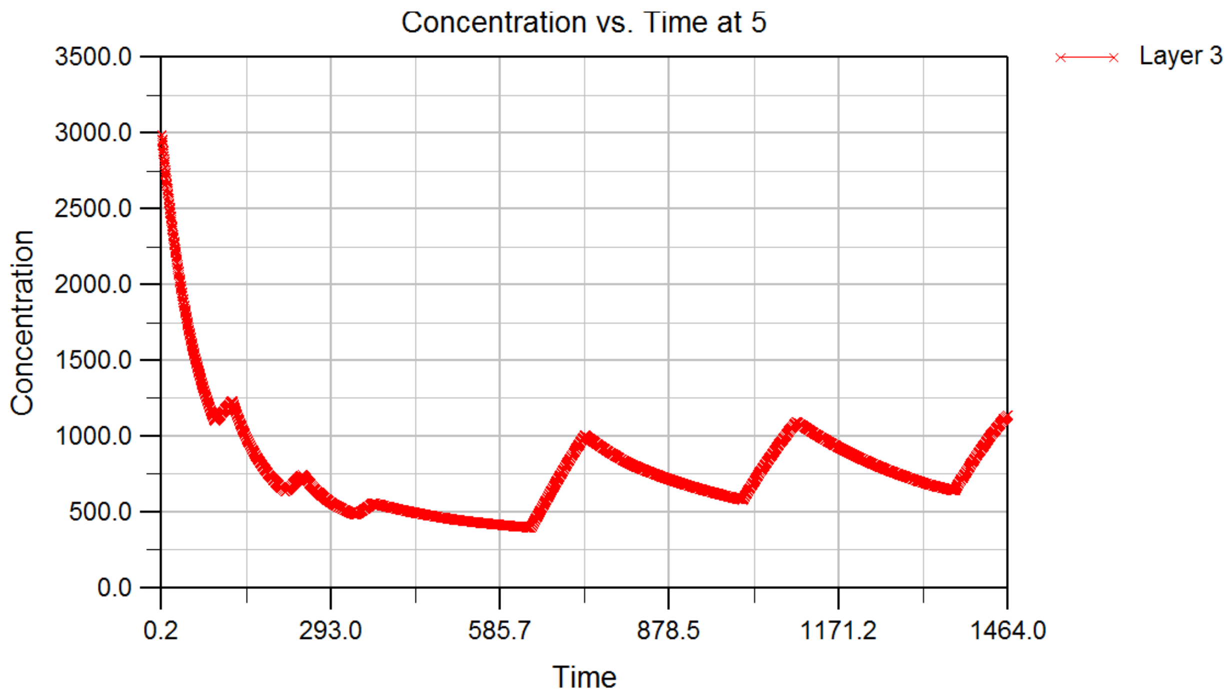
500.0
0.0
0.2
293.0
585.7
878.5
1171.2
1464.0
Time


Concentration vs. Time at 5
Layer 3
Concentration
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1500.0
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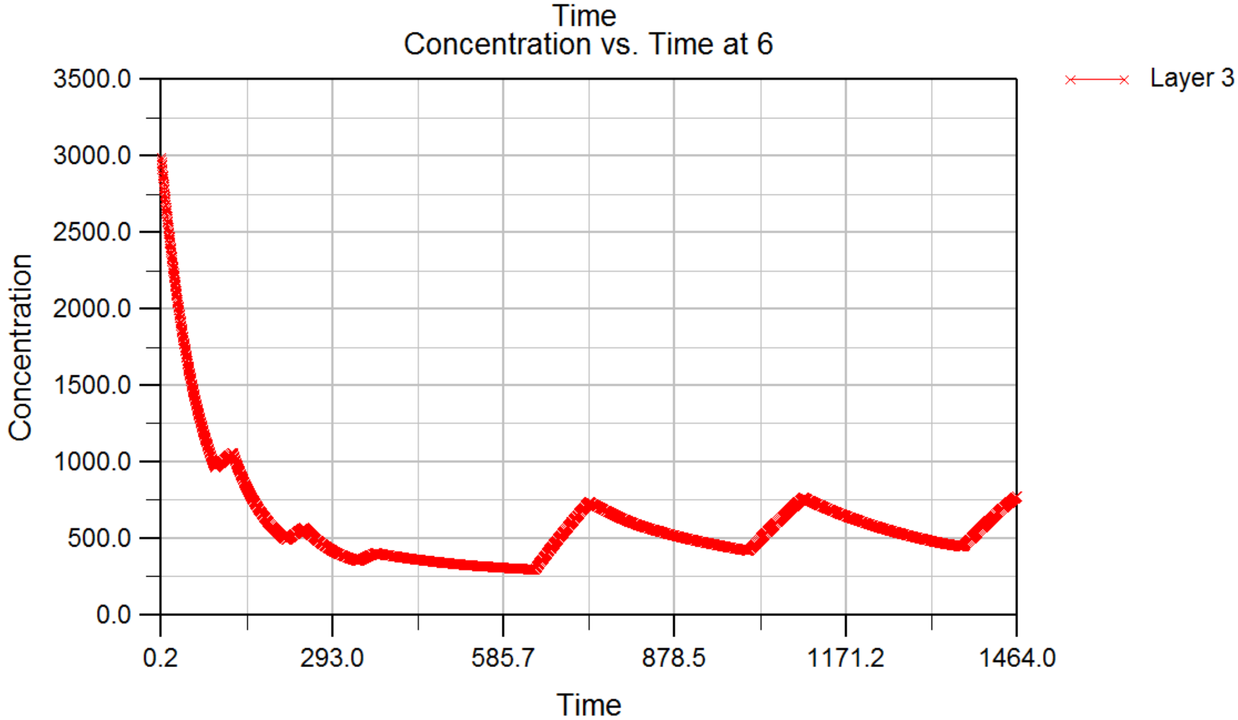
500.0
0.0
0.2
293.0
585.7
878.5
1171.2
1464.0
Time


Concentration vs. Time at 6
Layer 3
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2500.0
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1500.0
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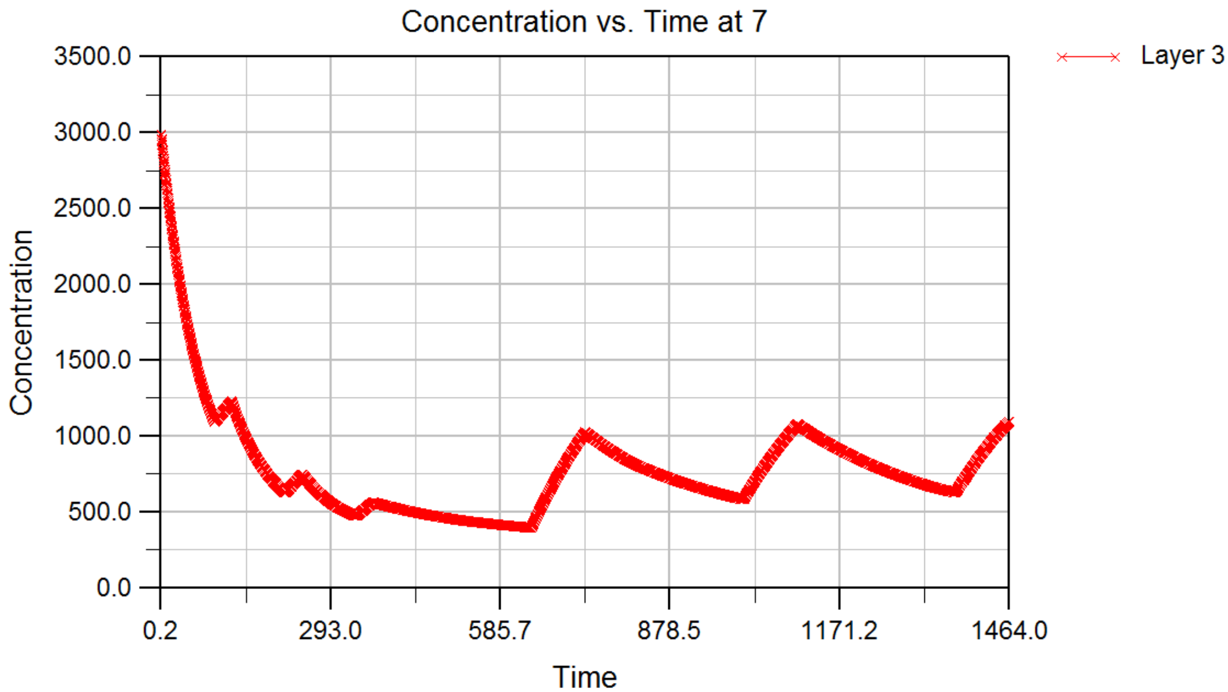
500.0
0.0
0.2
293.0
585.7
878.5
1171.2
1464.0
Time


Concentration vs. Time at 7
Layer 3
Concentration
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2500.0
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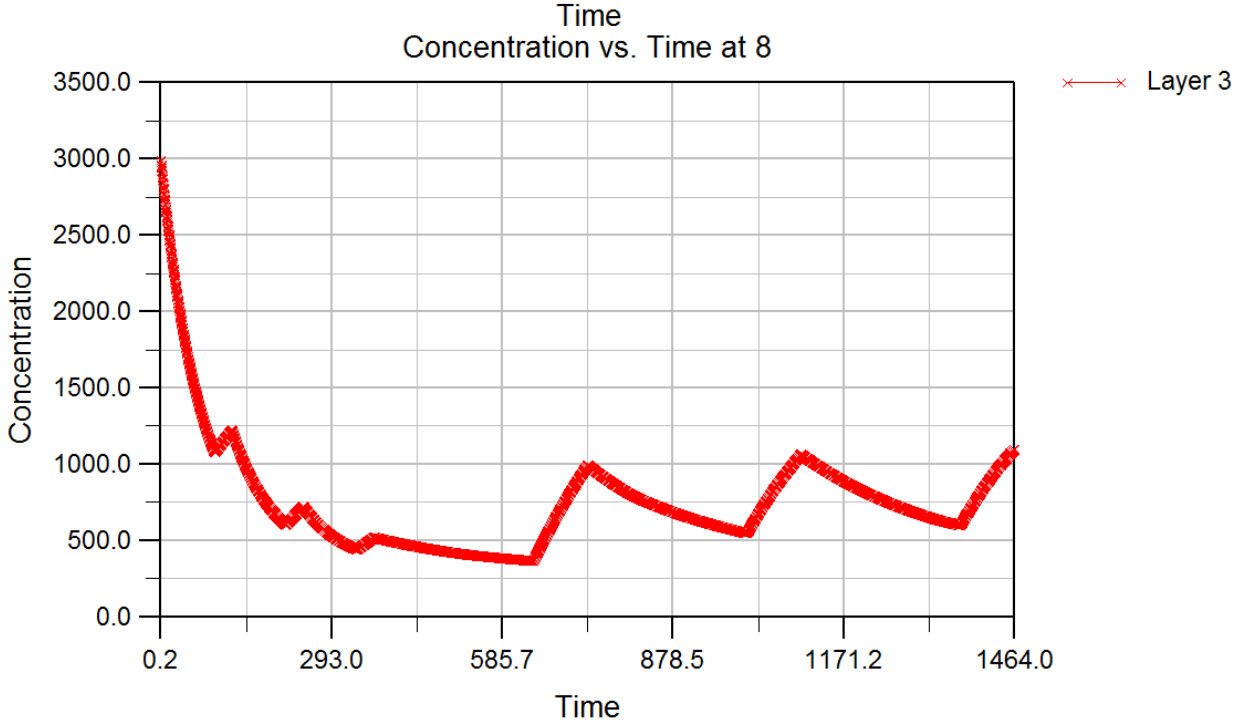
500.0
0.0
0.2
293.0
585.7
878.5
1171.2
1464.0
Time


Concentration vs. Time at 8
Layer 3
Concentration
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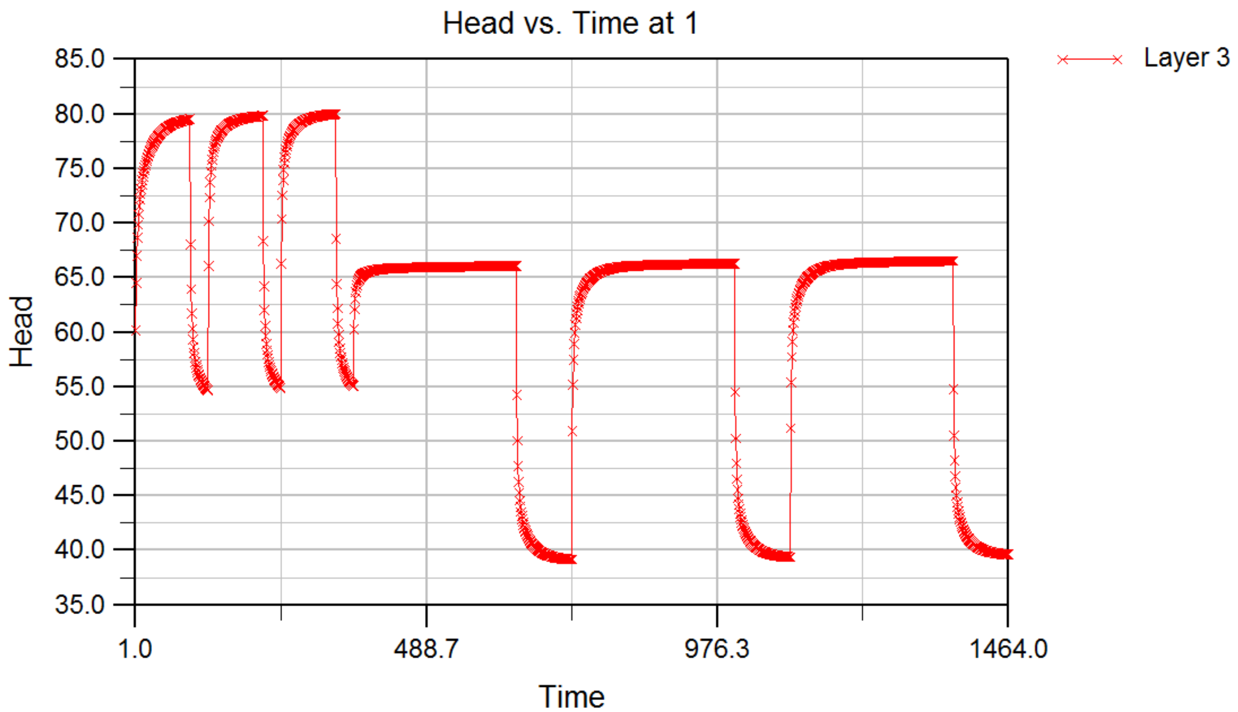
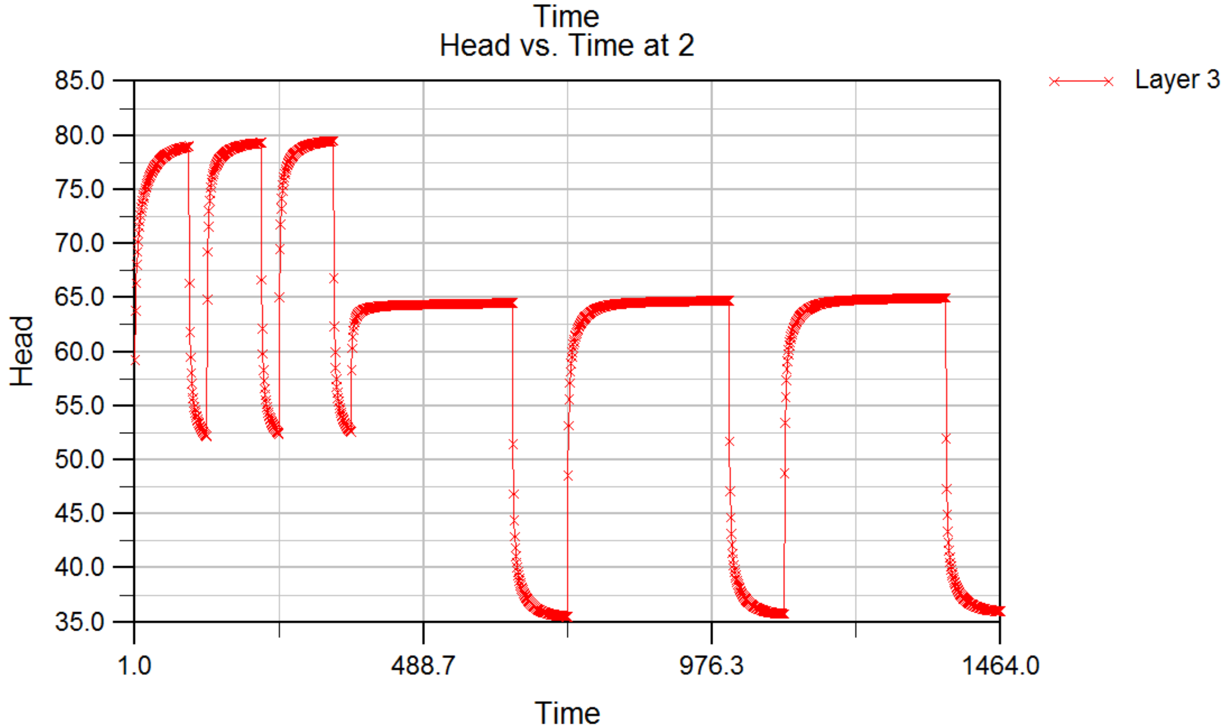
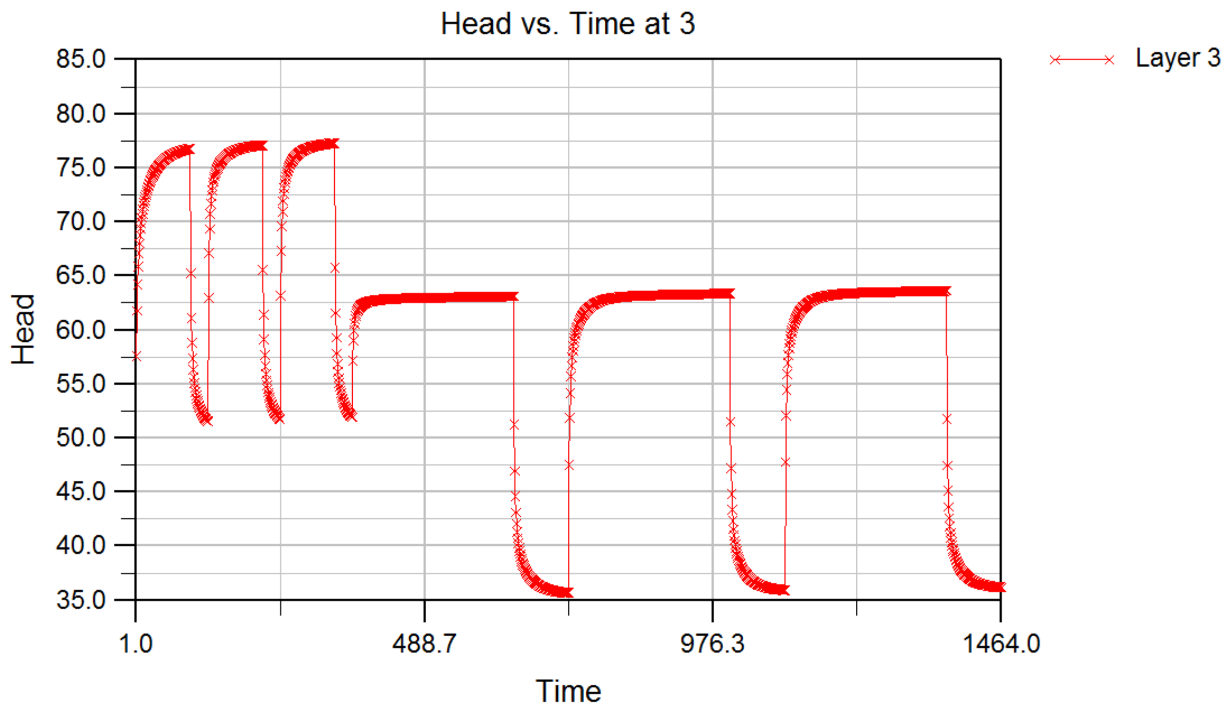
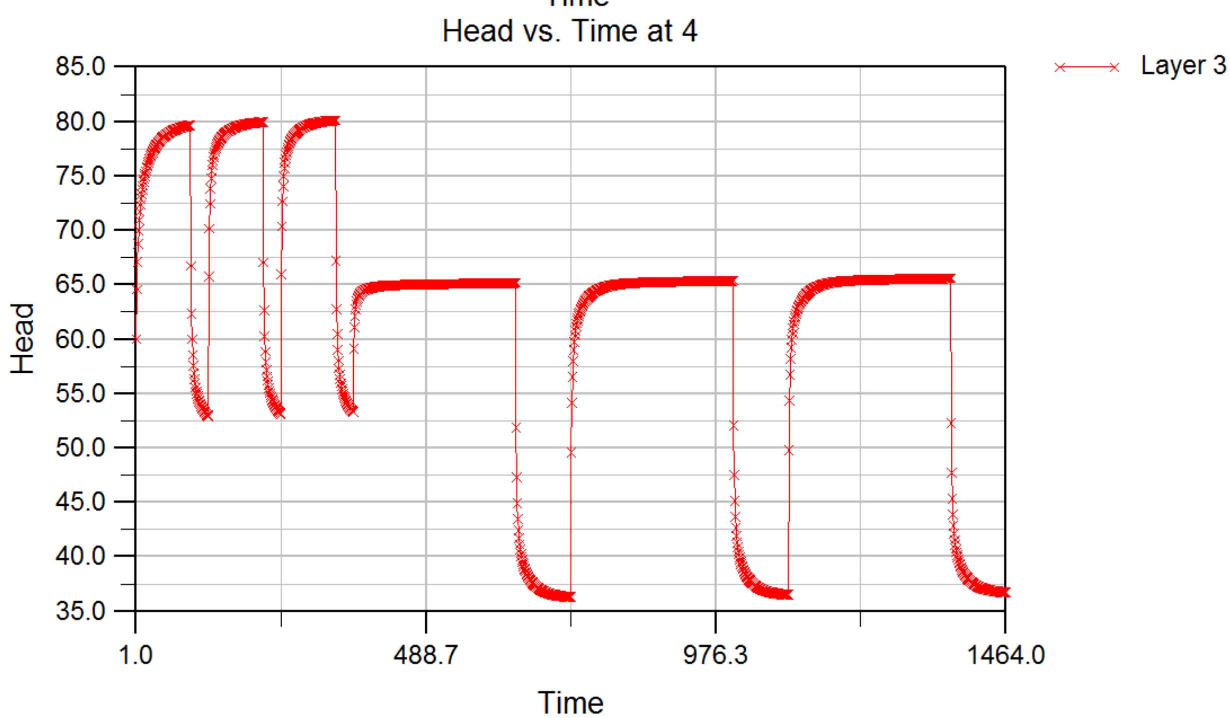
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.2
293.0
585.7
878.5
1171.2
1464.0
Time

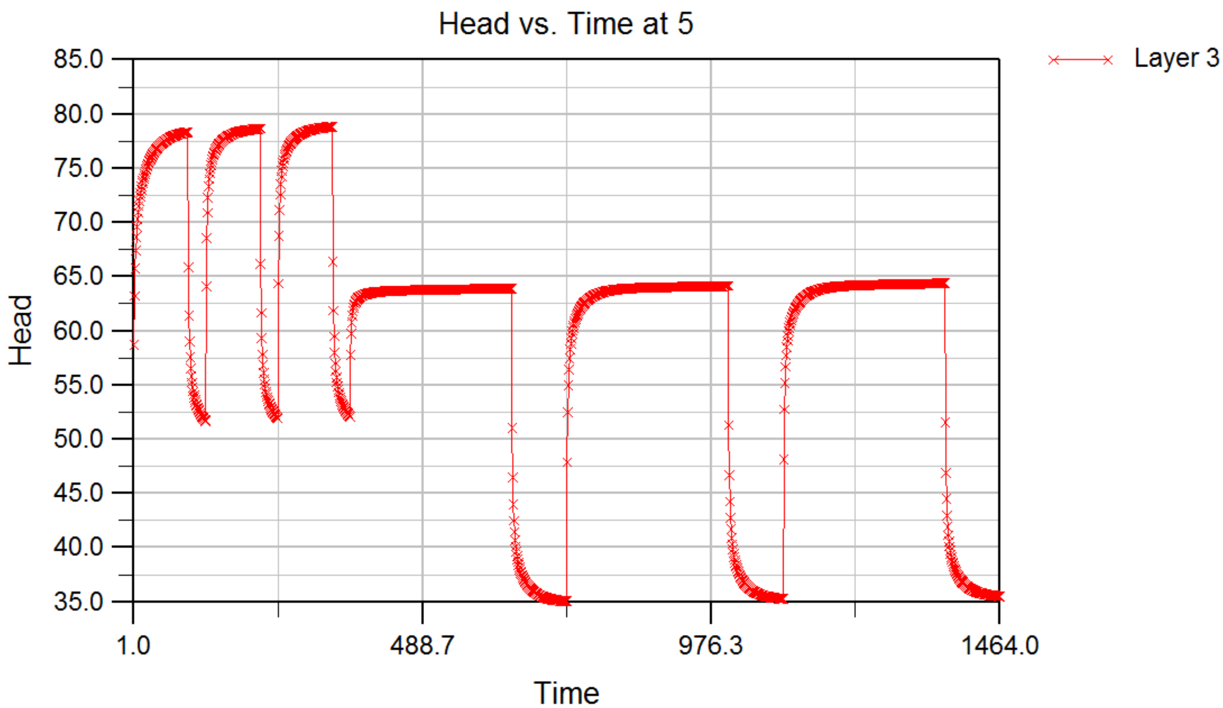
RUN 2 MODFLOW



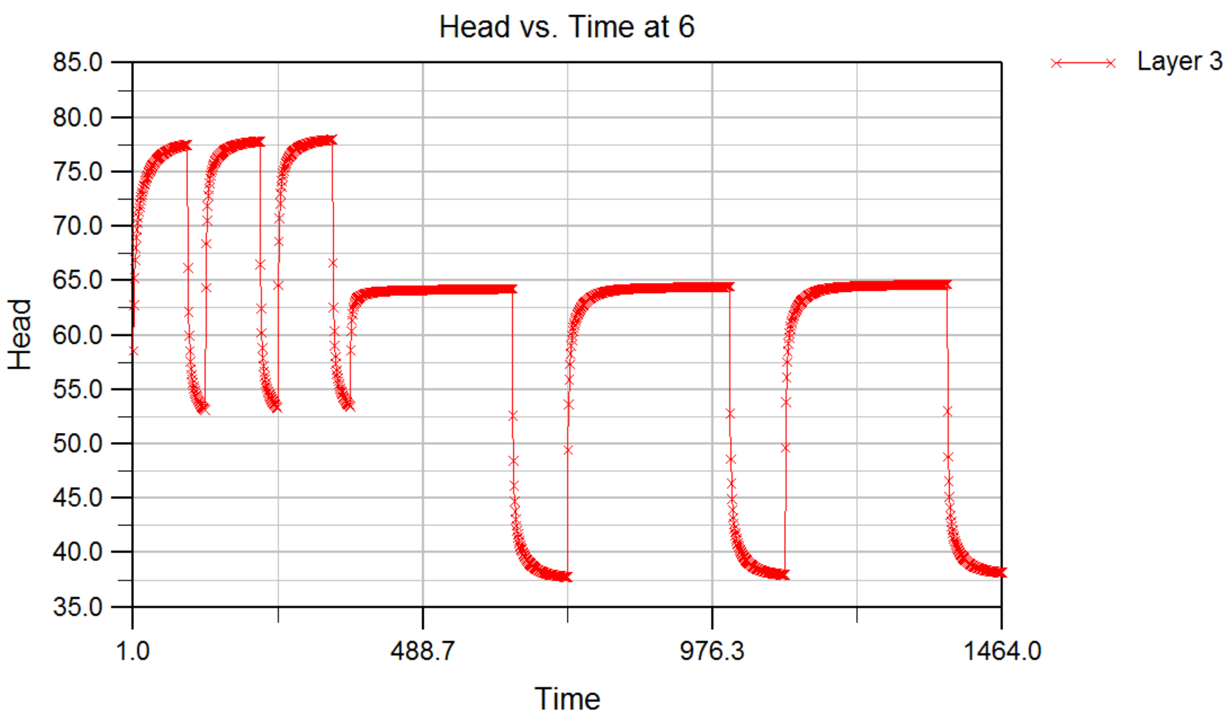



Head vs. Time at 3
Layer 3
Head
Time
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
1.0
488.7
976.3
1464.0

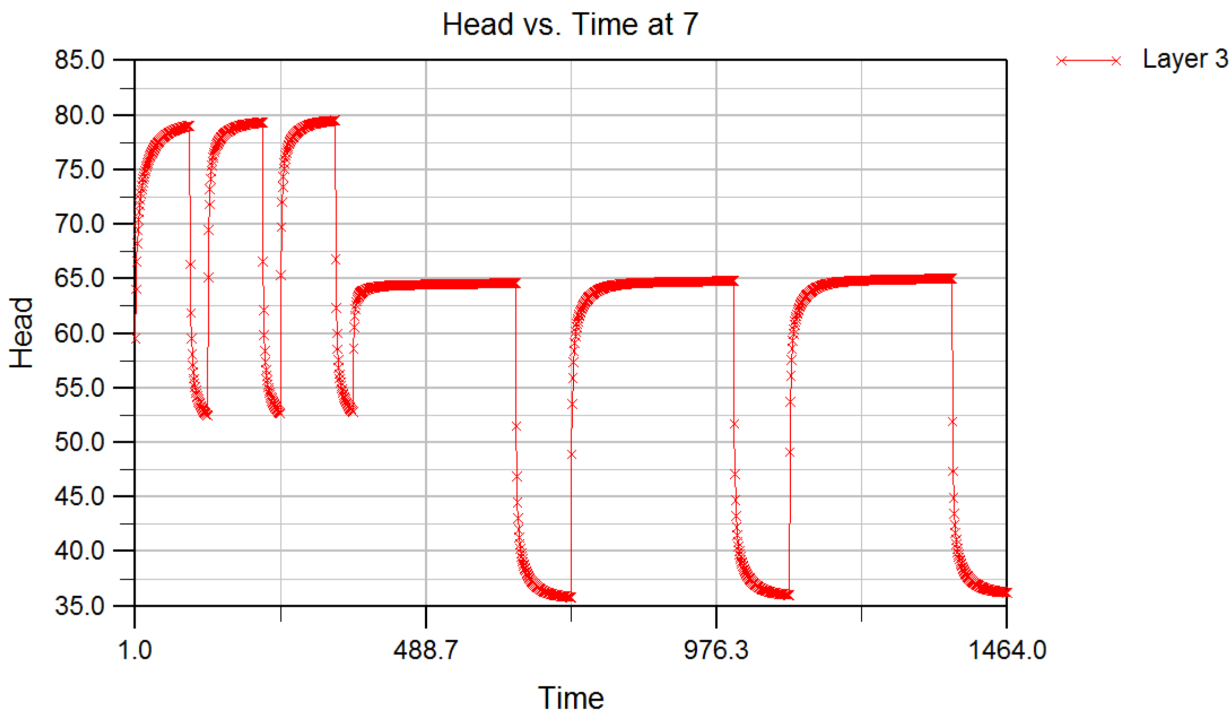

Head vs. Time at 4
Layer 3
Head
Time
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
1.0
488.7
976.3
1464.0

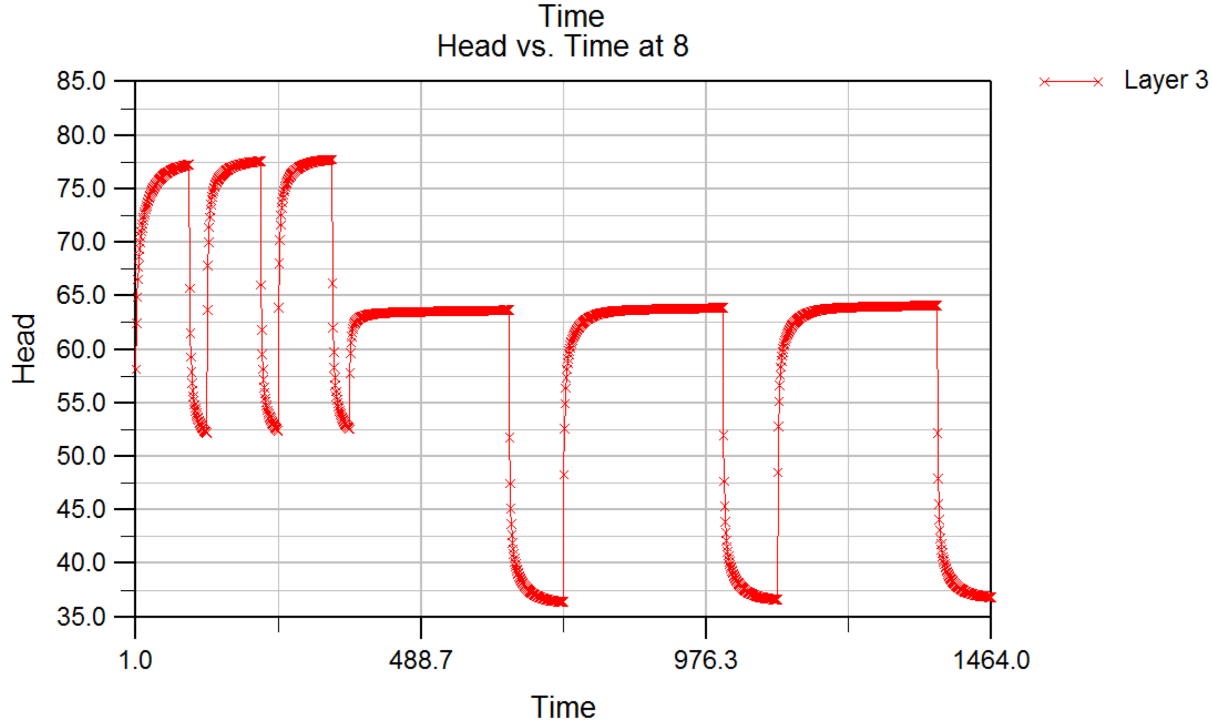


Head vs. Time at 5
Layer 3
Head
Time
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
1.0
488.7
976.3
1464.0

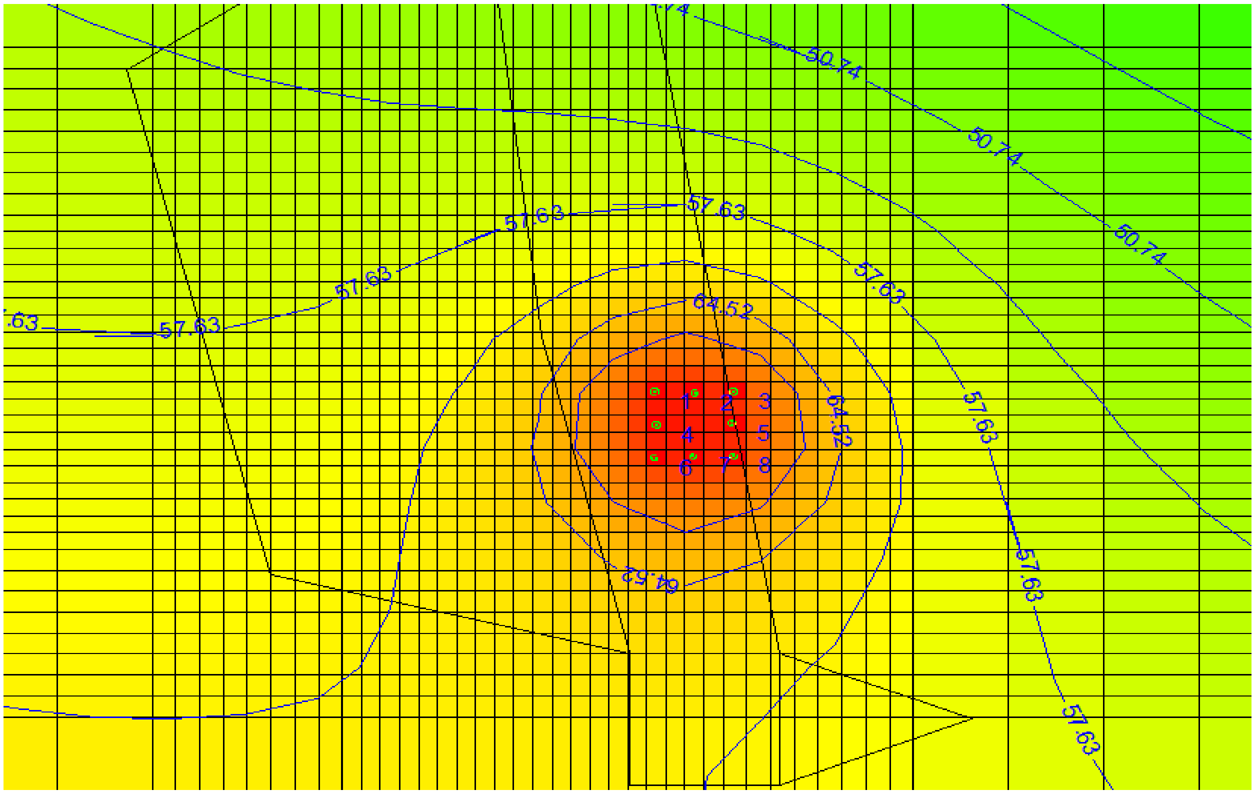


Head vs. Time at 6
Layer 3
Head
Time
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
1.0
488.7
976.3
1464.0

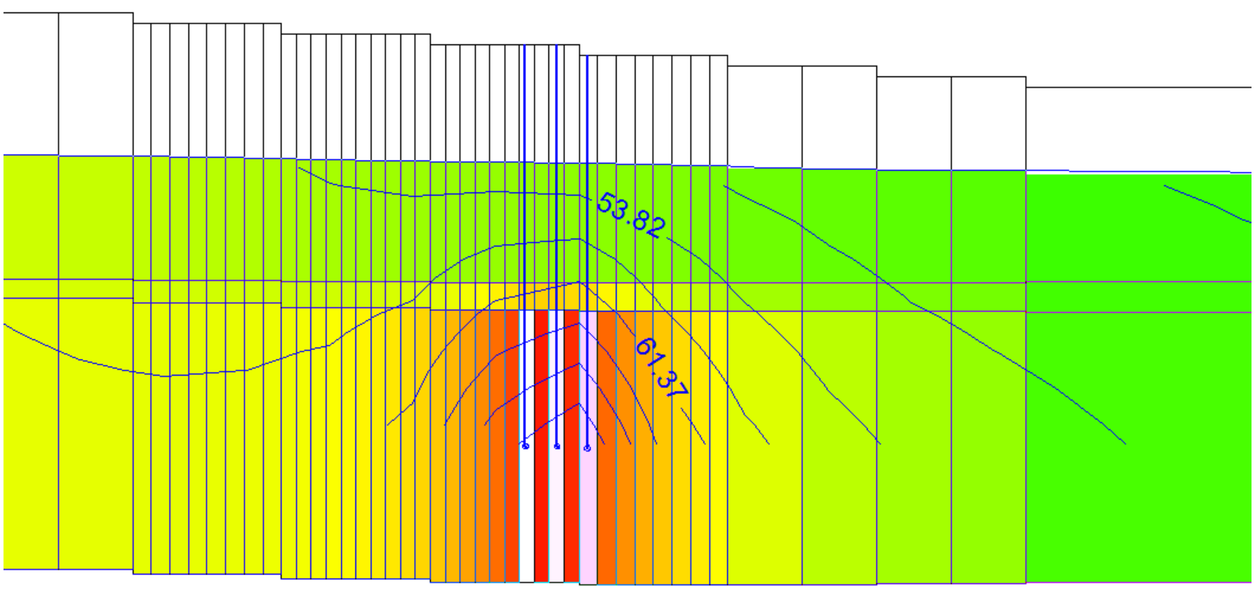

Head vs. Time at 7
Layer 3
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
Head
1.0
488.7
976.3
1464.0
Time


Head vs. Time at 8
Layer 3
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
Head
1.0
488.7
976.3
1464.0
Time

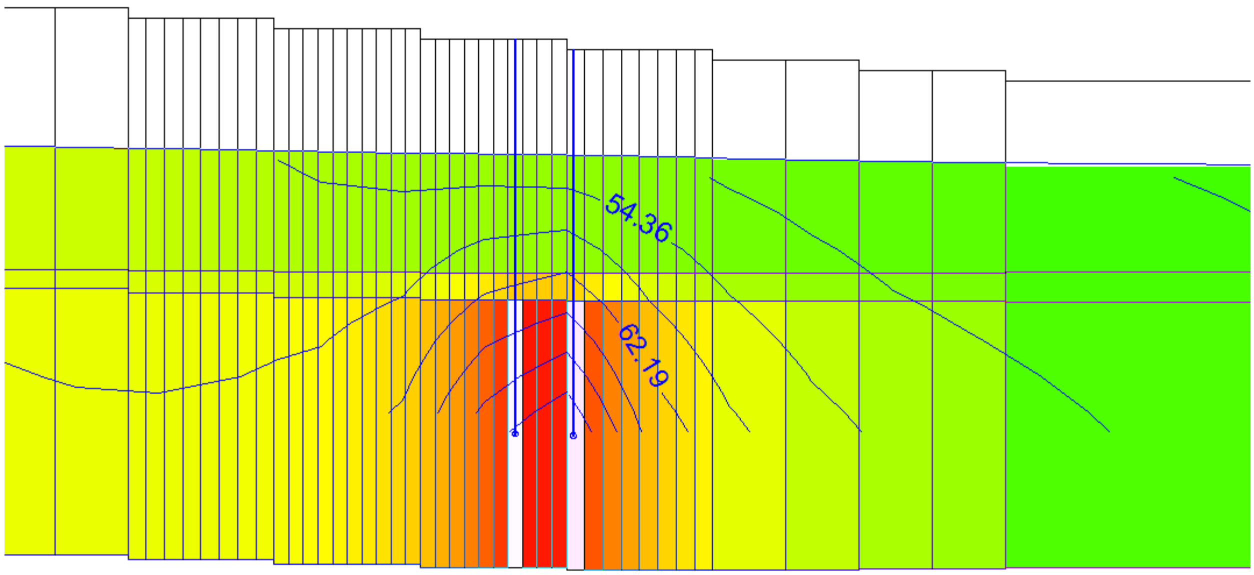
STRESS PERIOD (1-12)



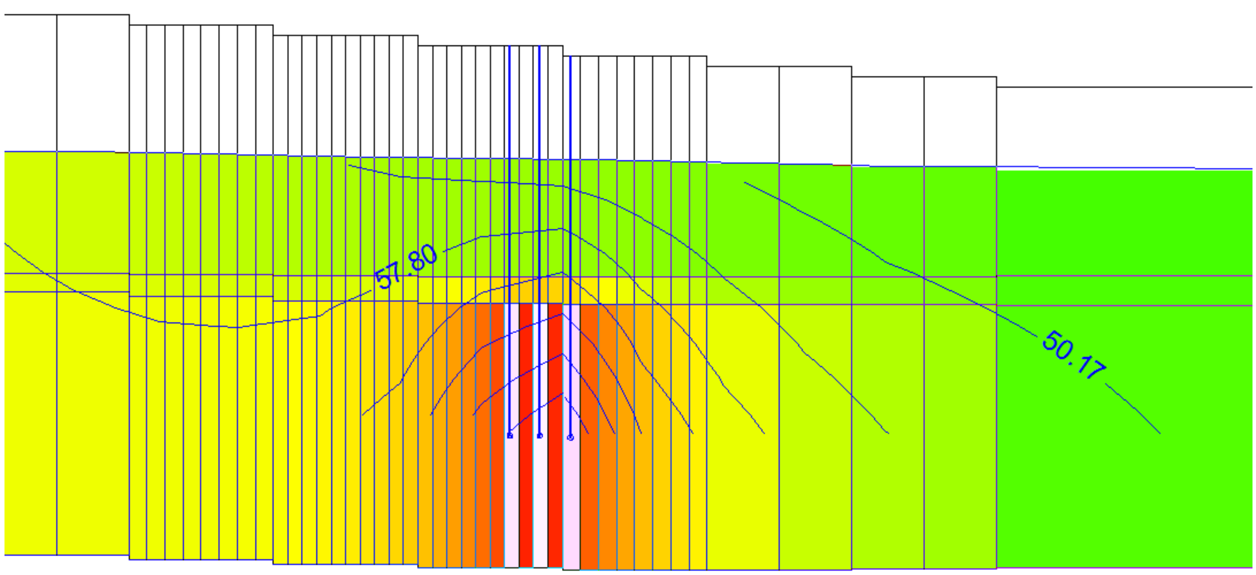
Cross-Section along Row 24



Cross-Section along Row 26



Cross-Section along Row 28



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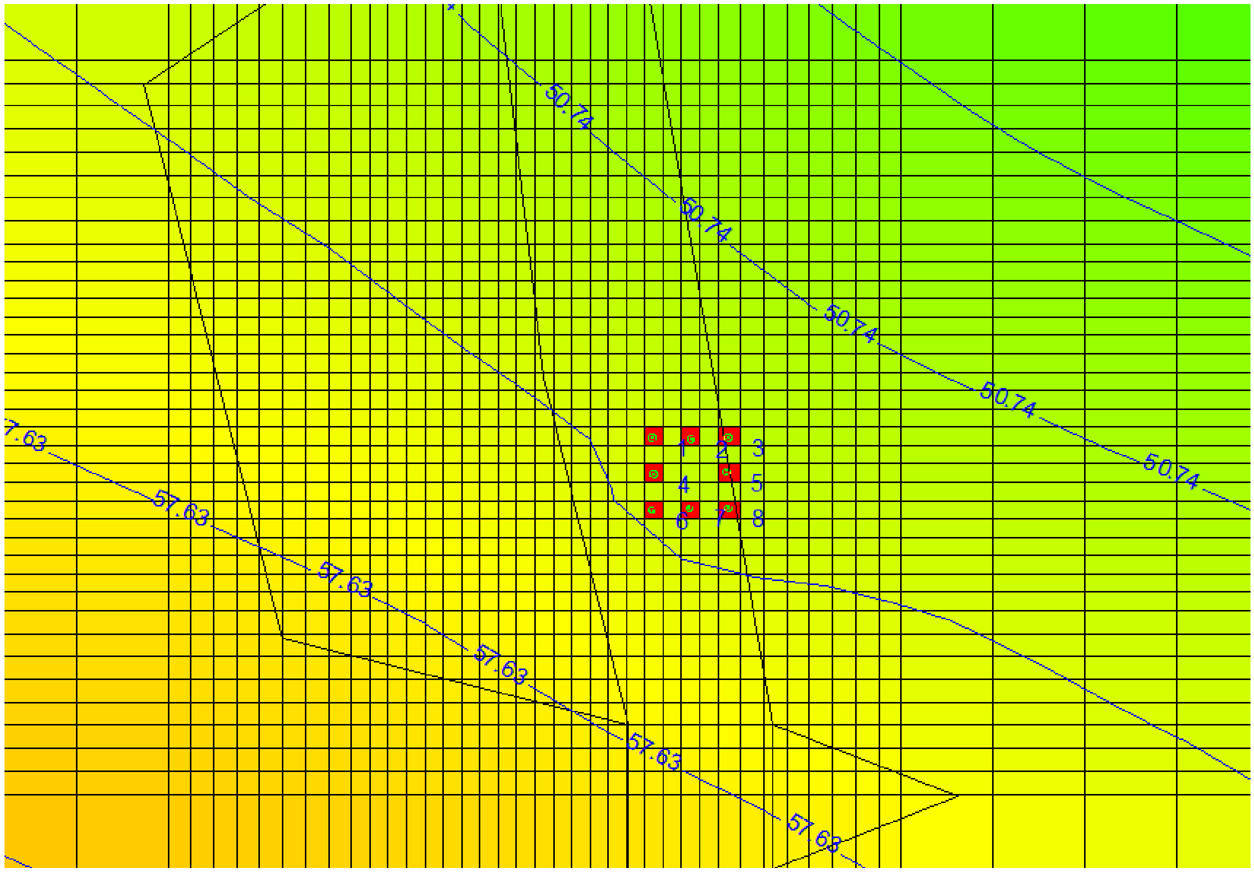
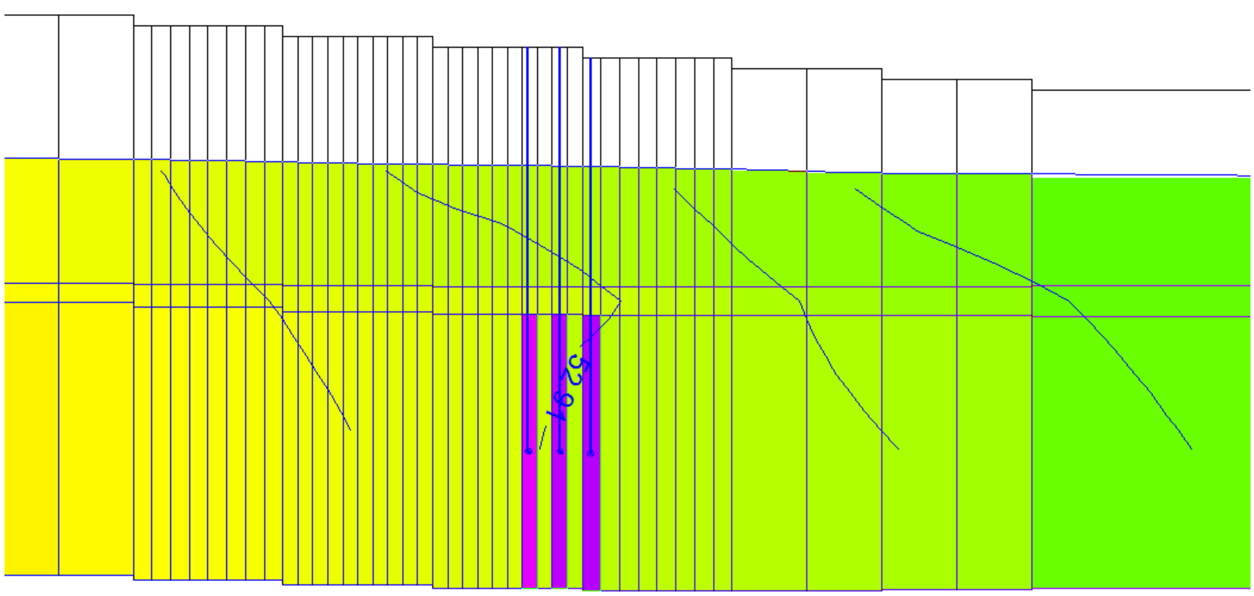


Cross-Section along Row 24



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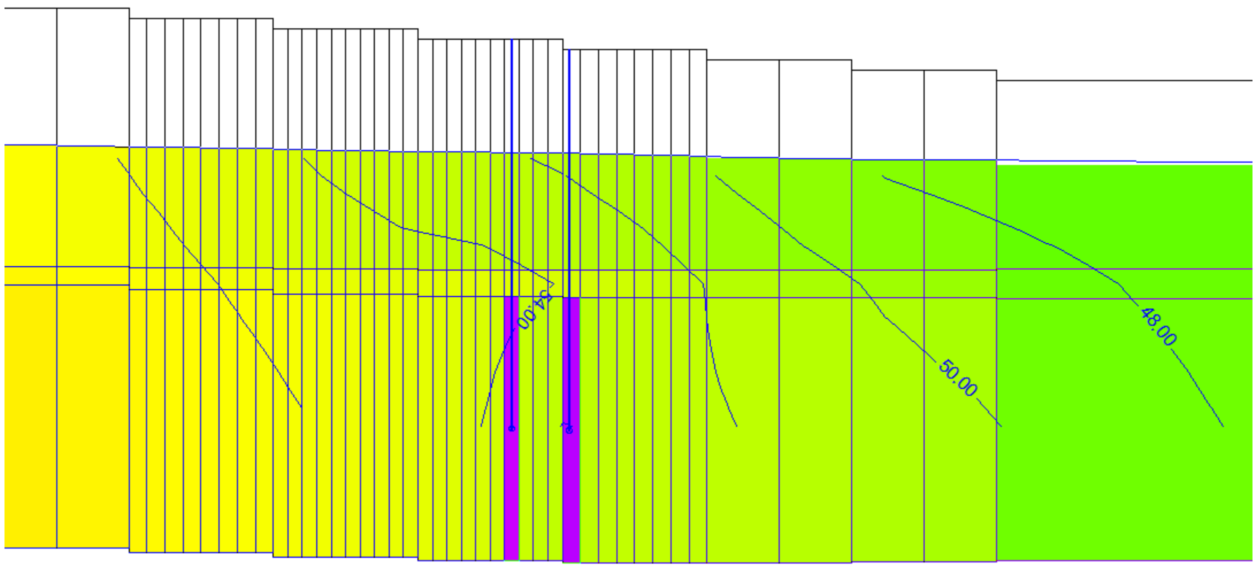
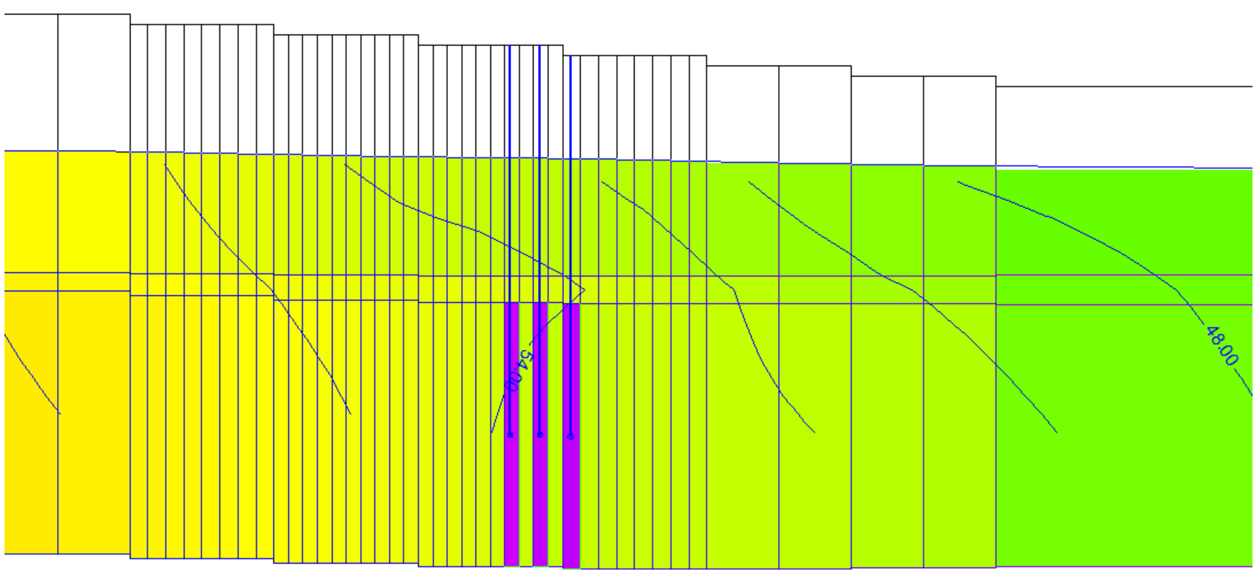


Cross-Section along Row 28



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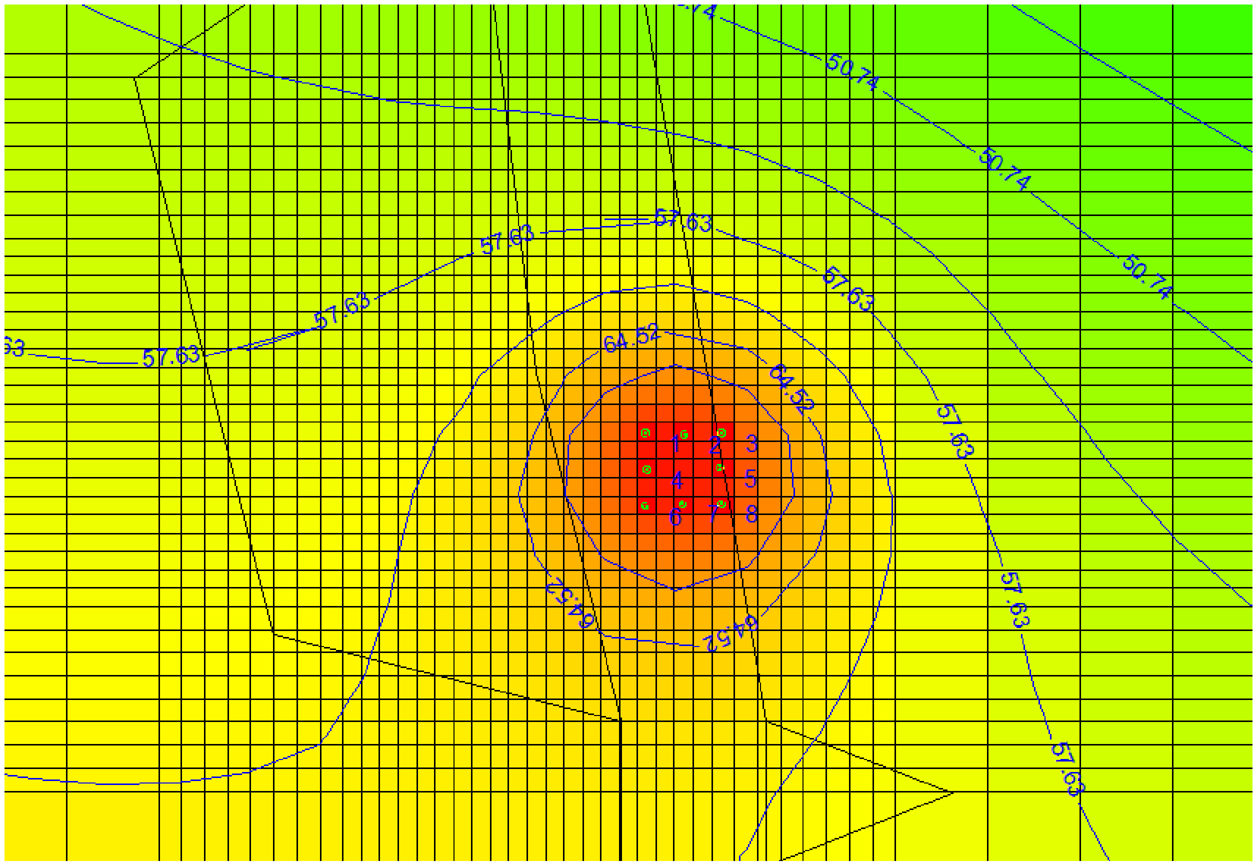
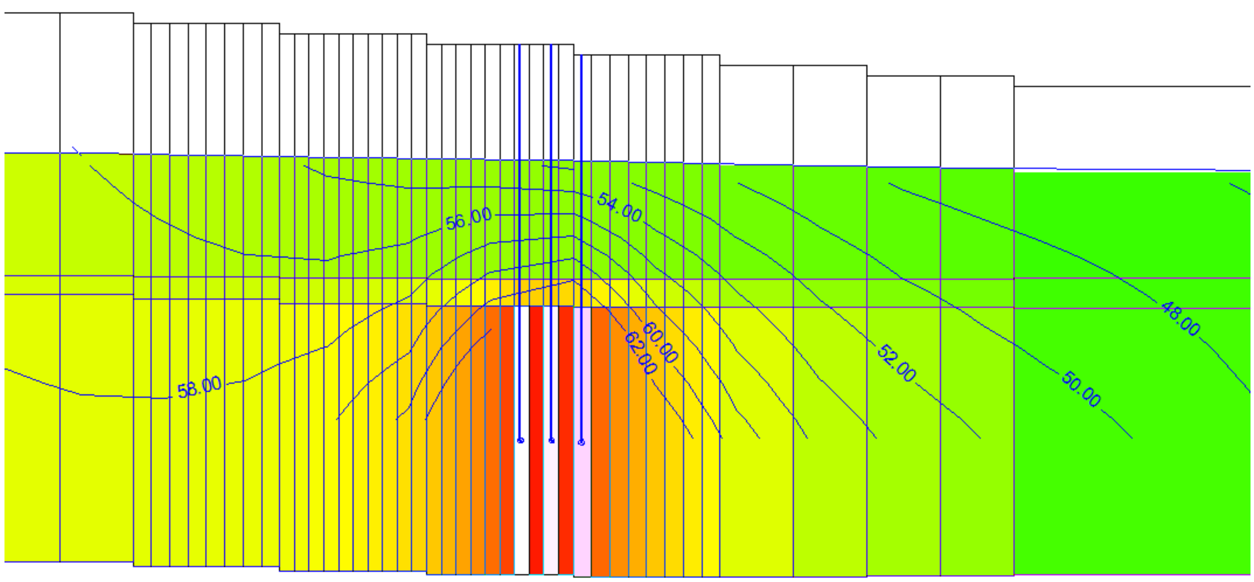
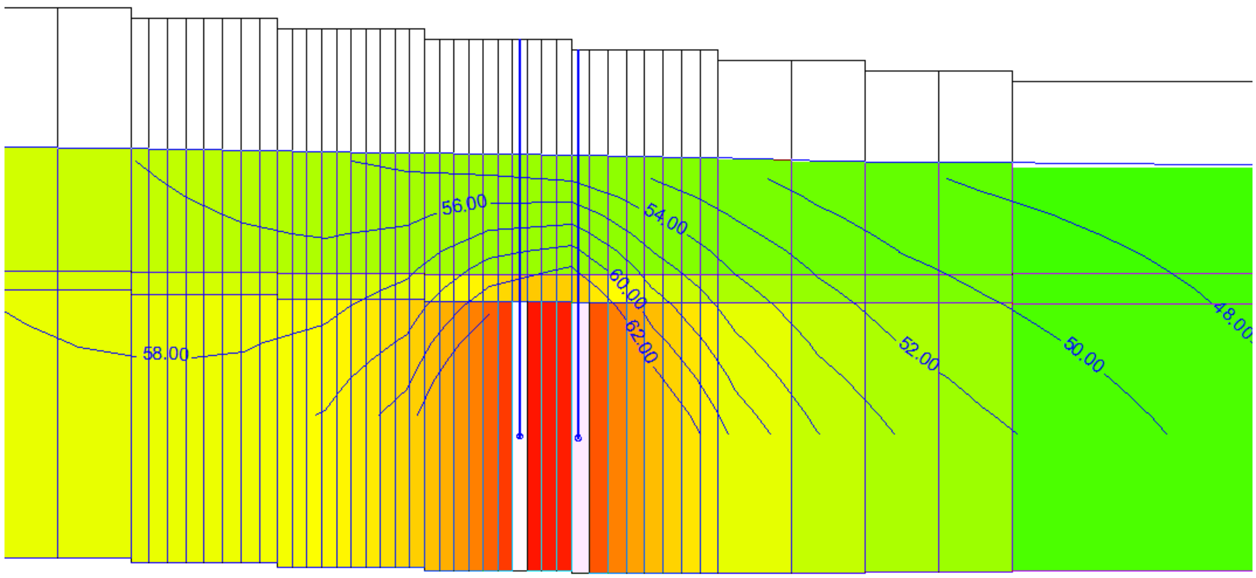


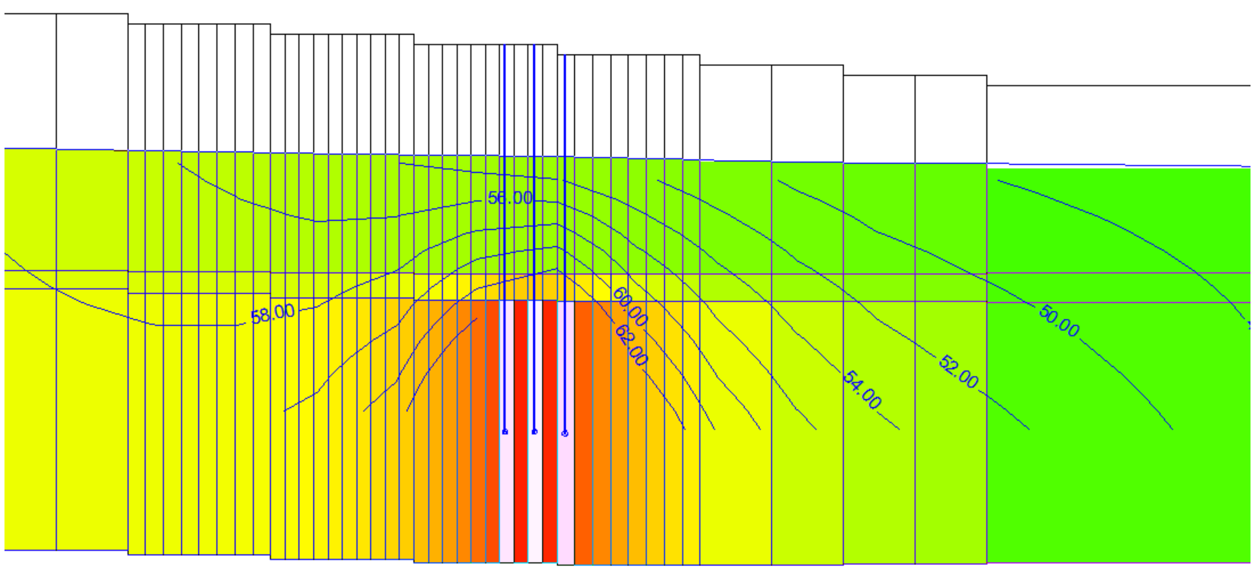
Cross-Section along Row 24



Cross-Section along Row 26



Cross-Section along Row 28



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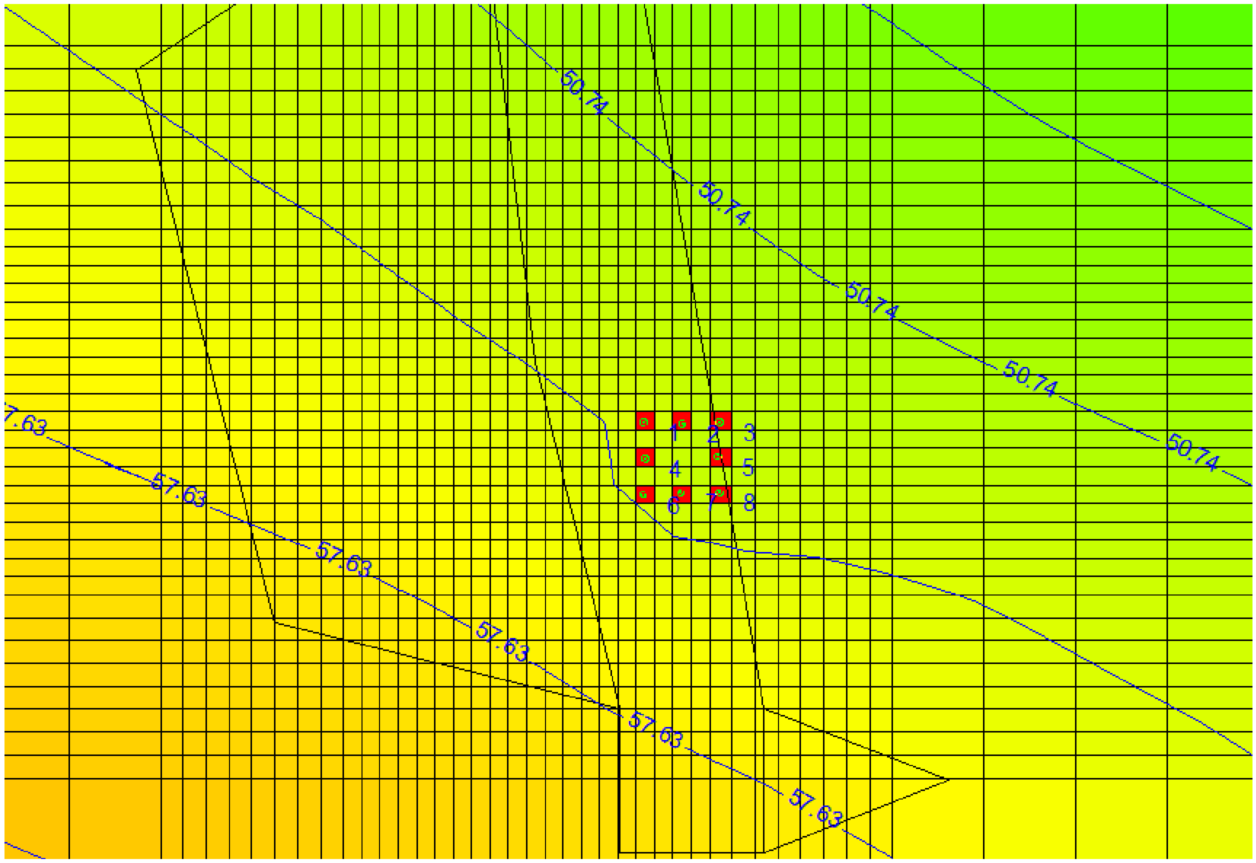
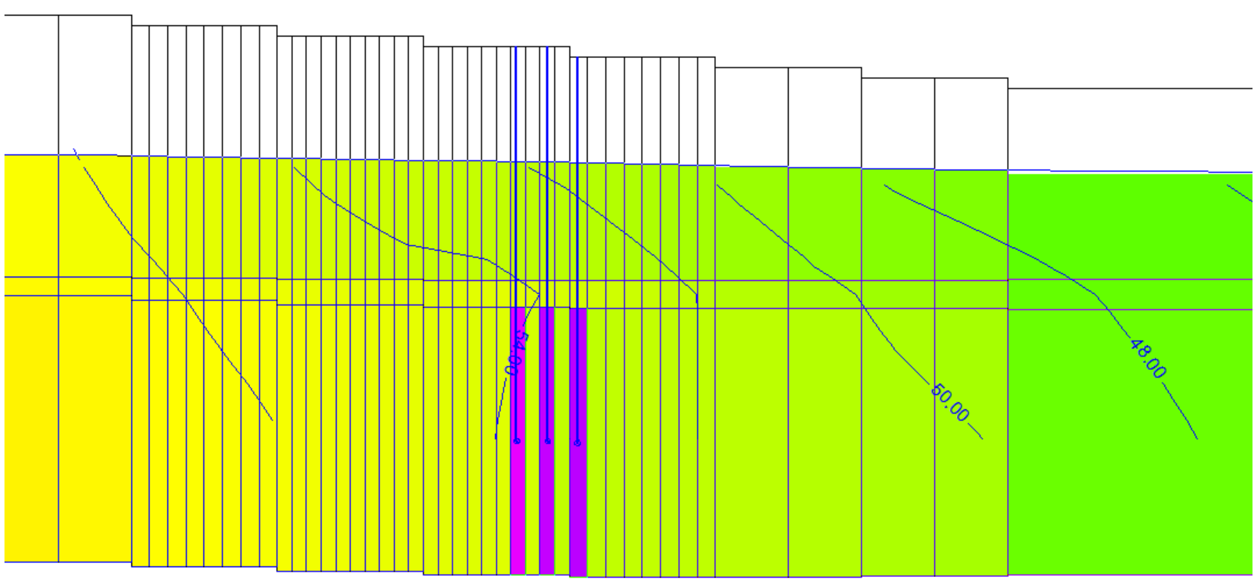


Cross-Section along Row 24



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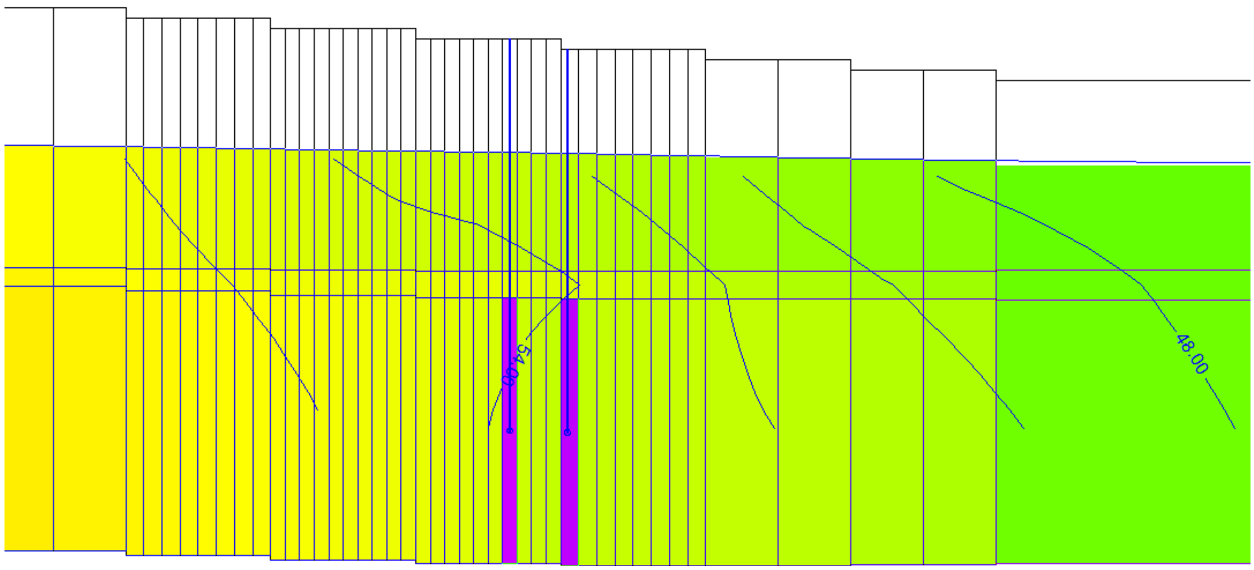
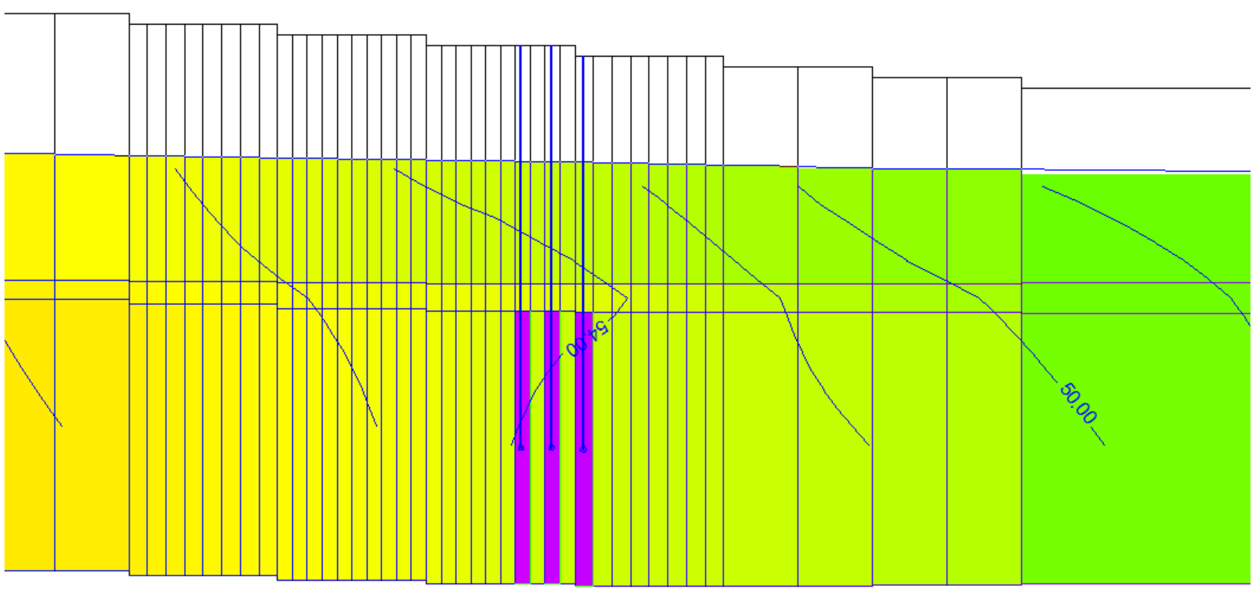


Cross-Section along Row 28



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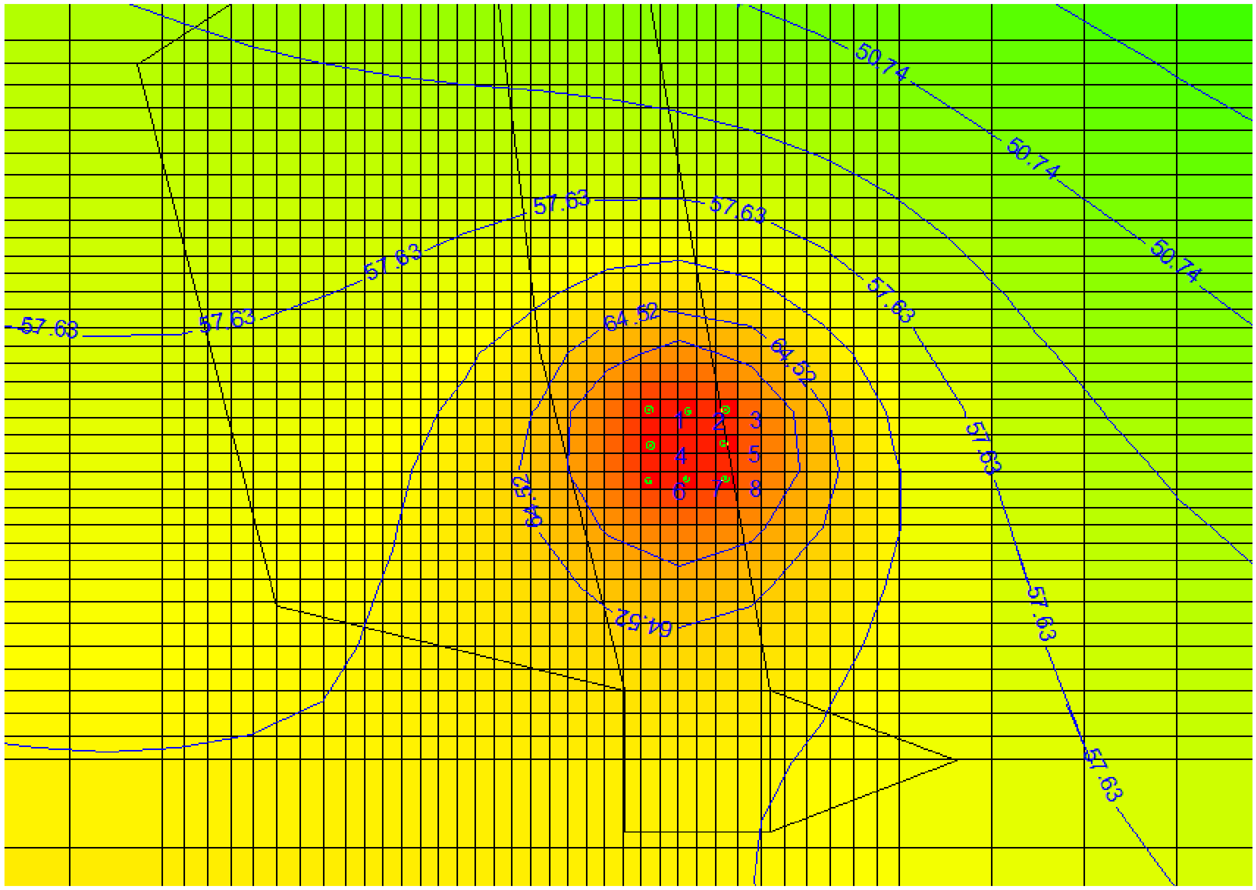
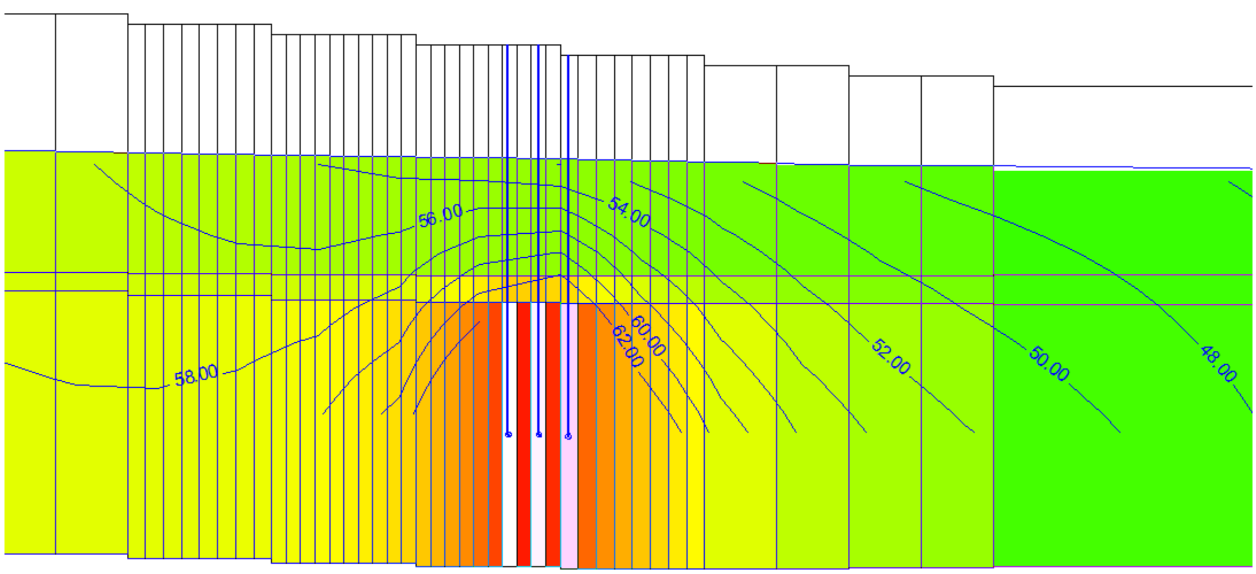


Cross-Section along Row 24



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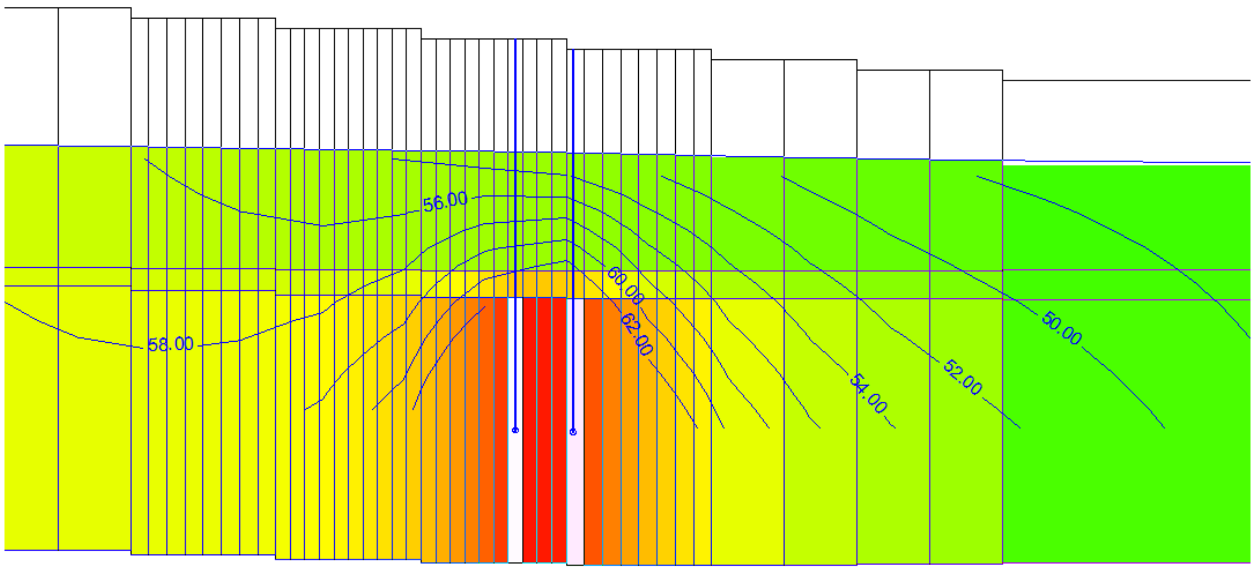
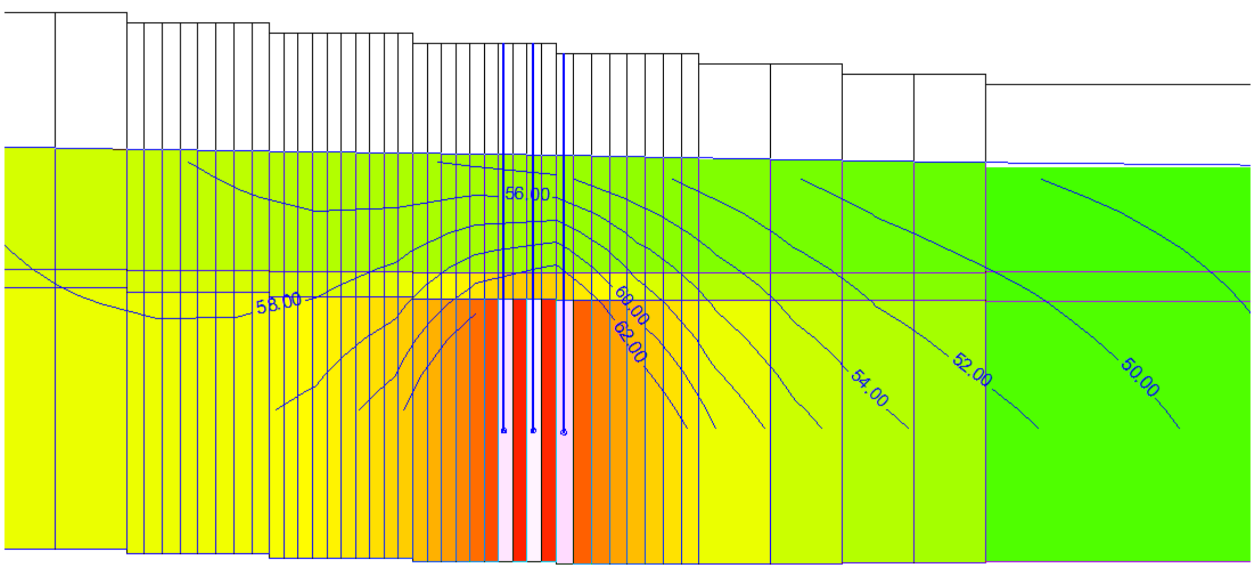


Cross-Section along Row 28



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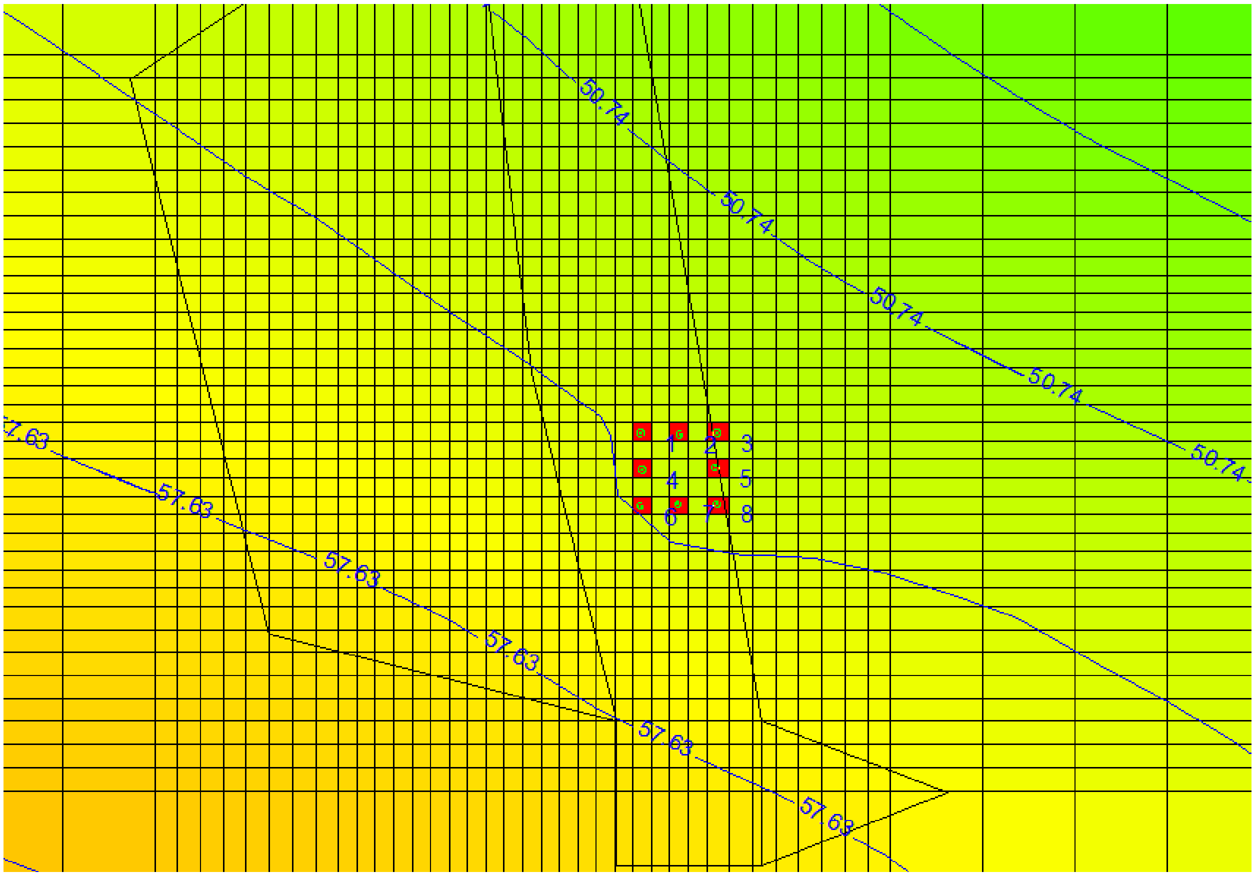

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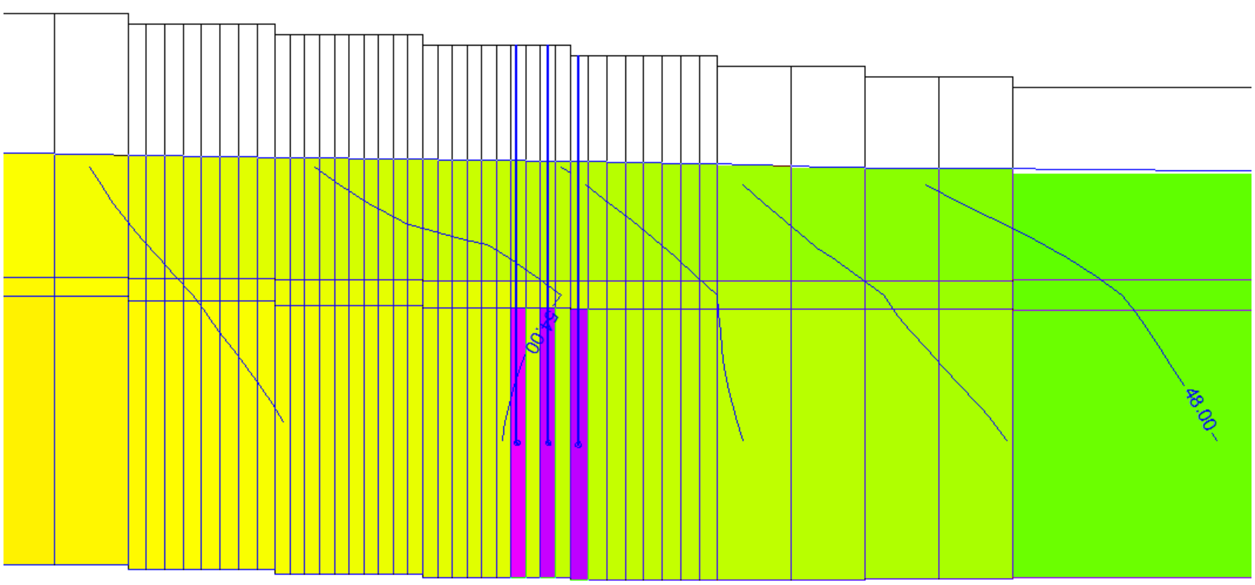
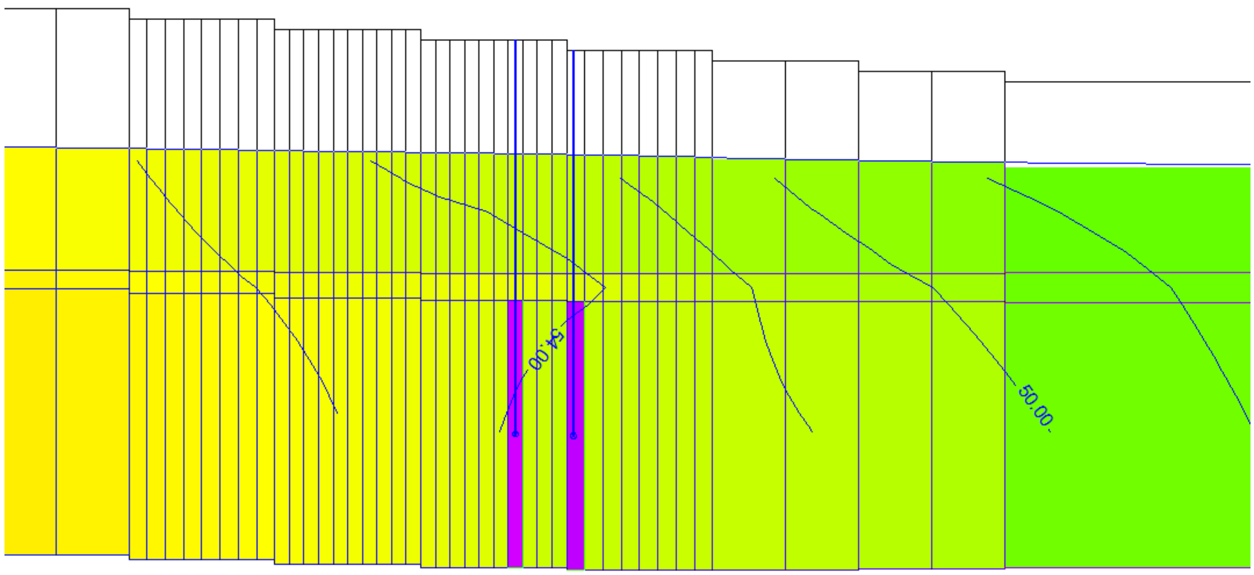


Cross-Section along Row 26



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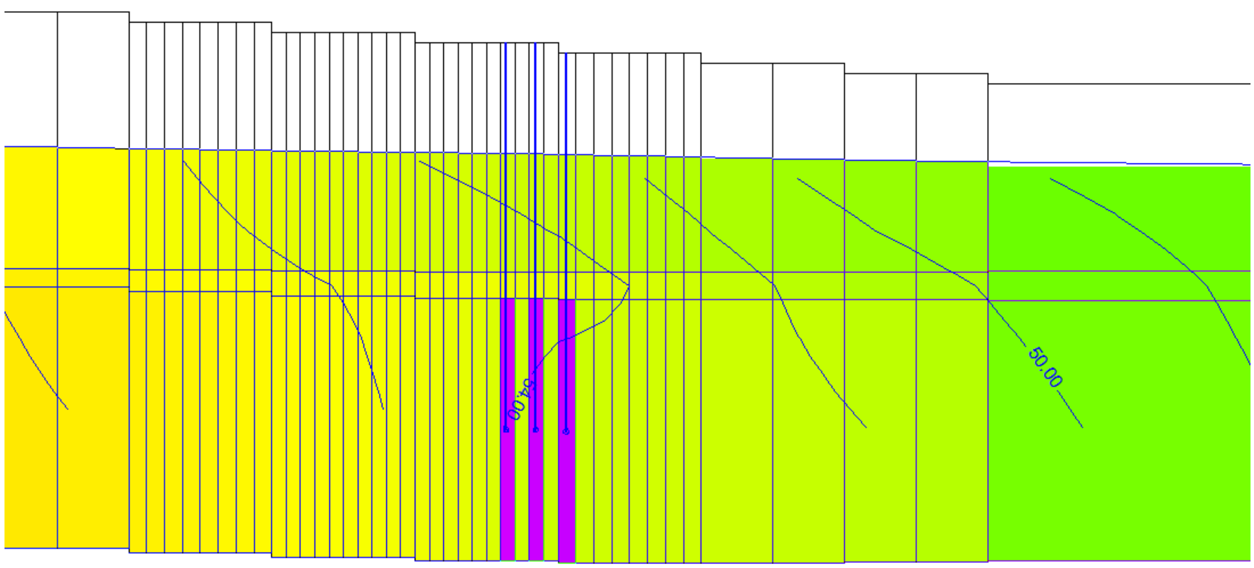

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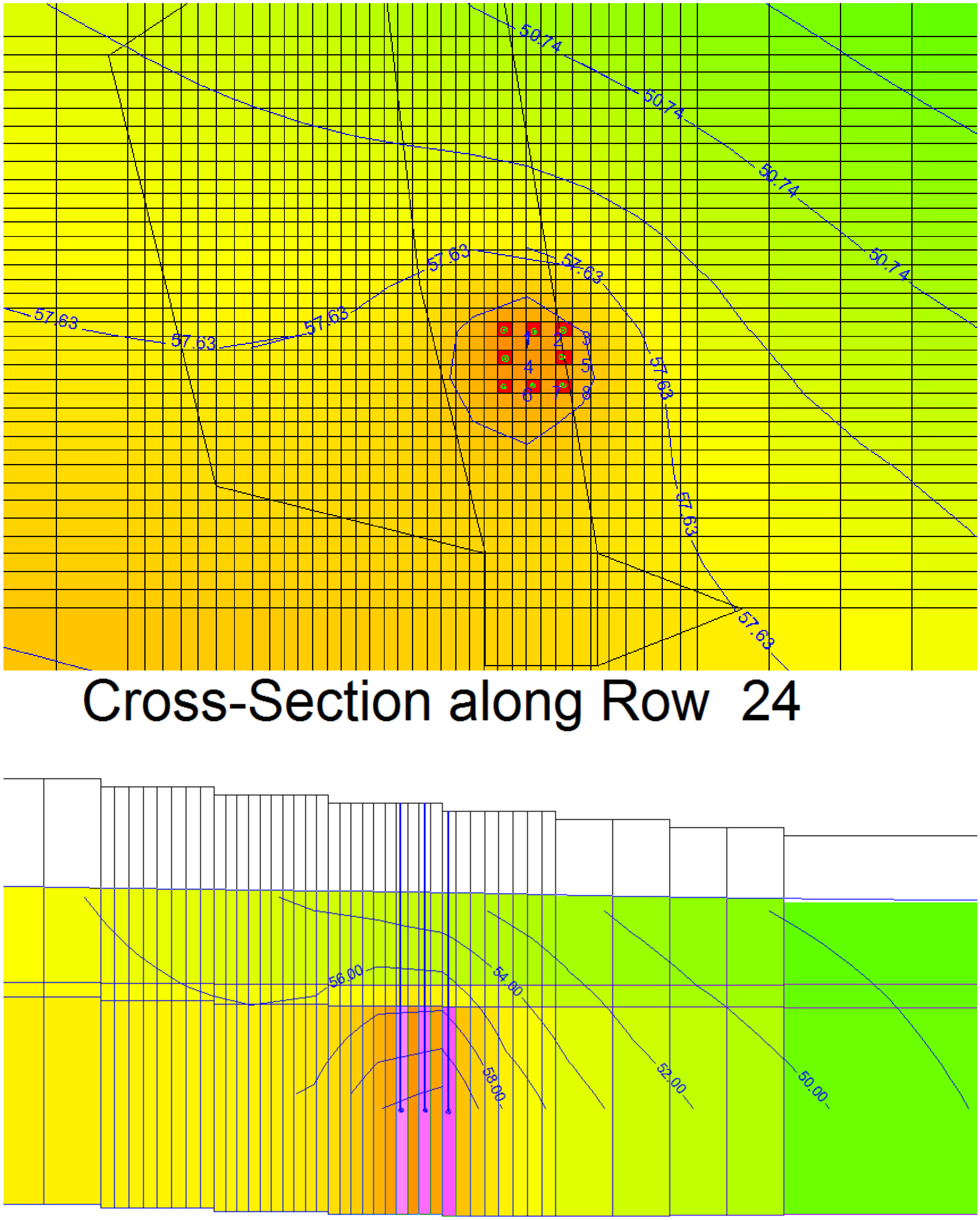
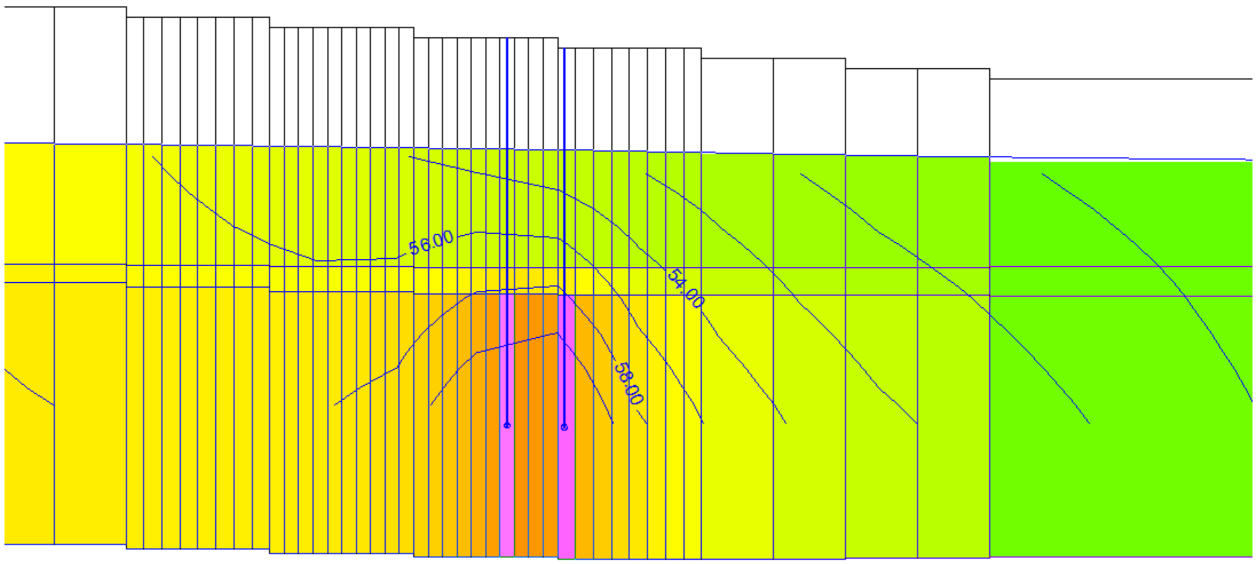


50.74
57.63
1
2
3
4
5
6
7
8
Cross-Section along Row 24
56.00
54.00
58.00
52.00
50.00

Cross-Section along Row 26



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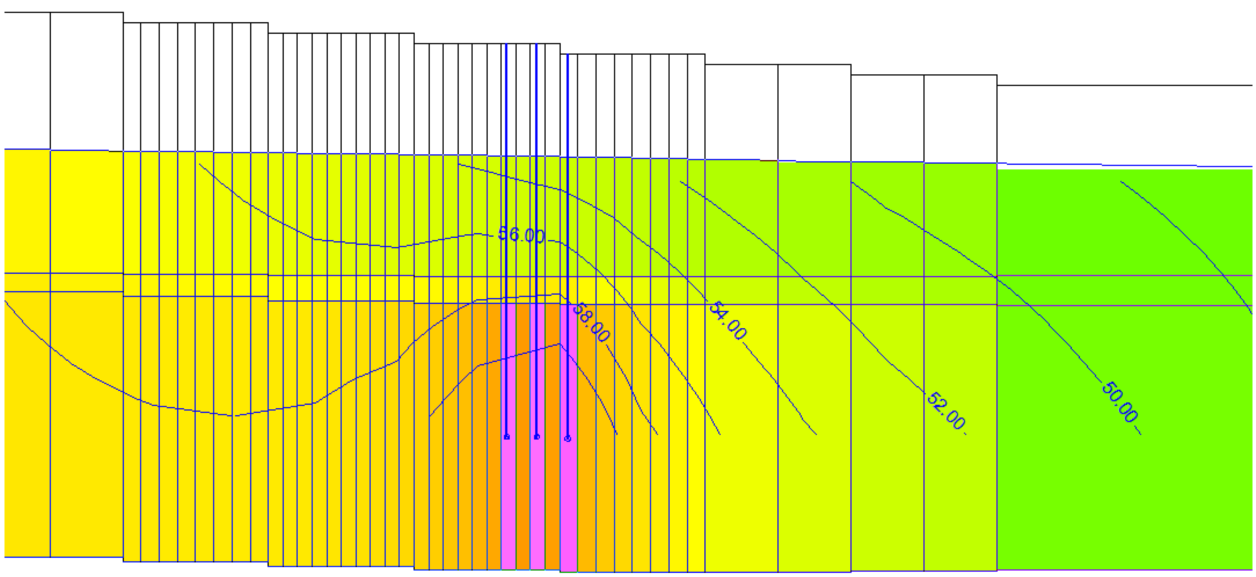

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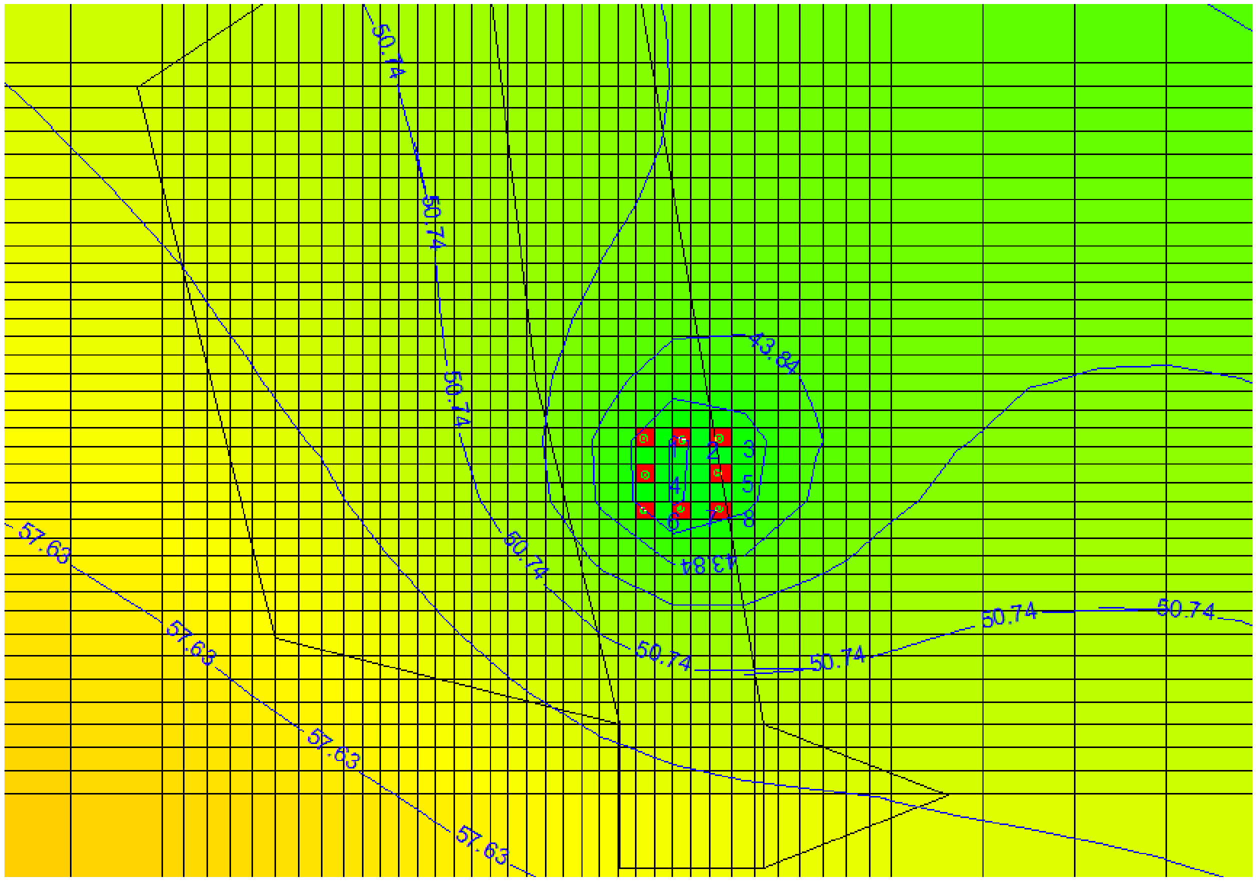
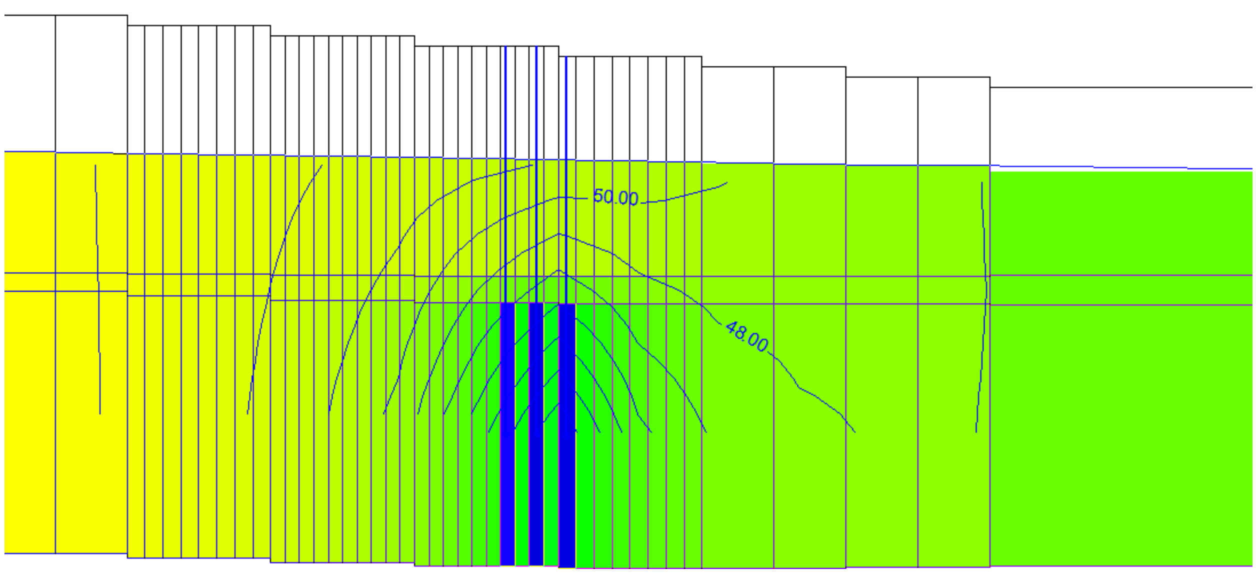
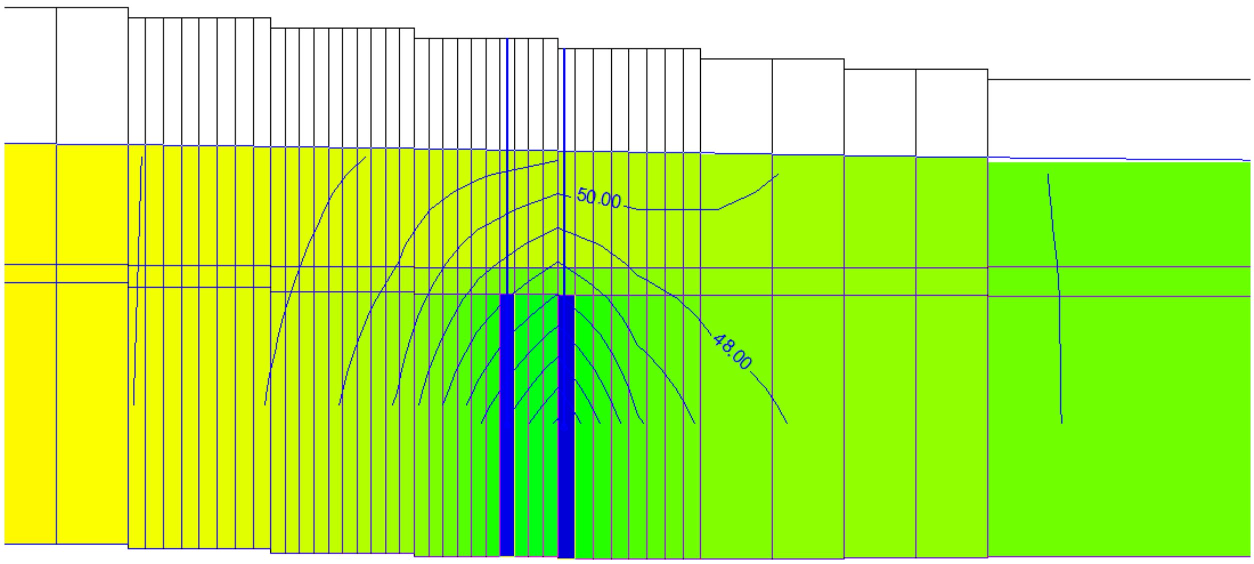


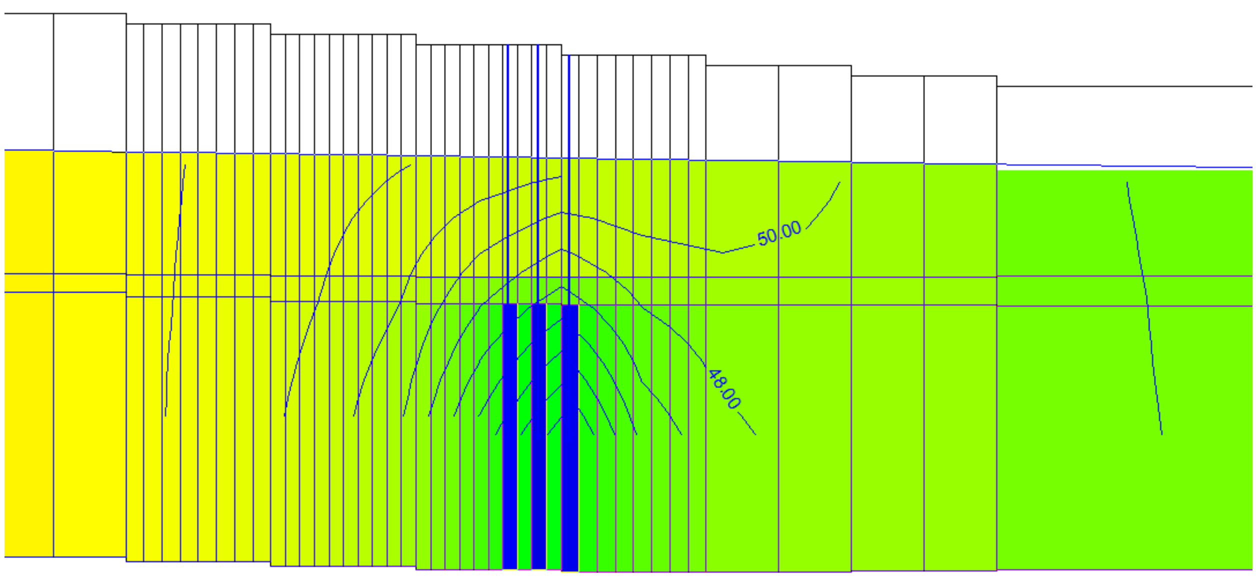
Cross-Section along Row 24



Cross-Section along Row 26



Cross-Section along Row 28



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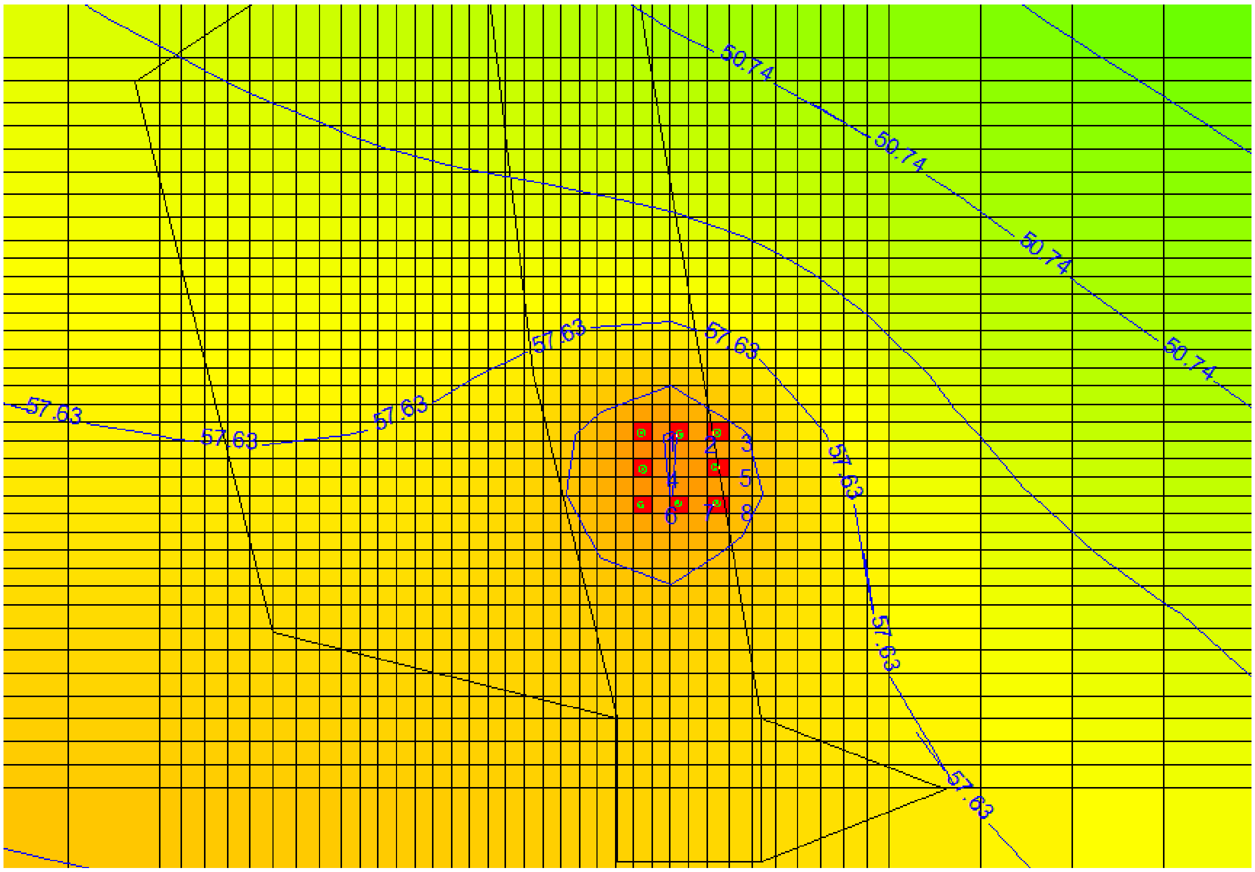

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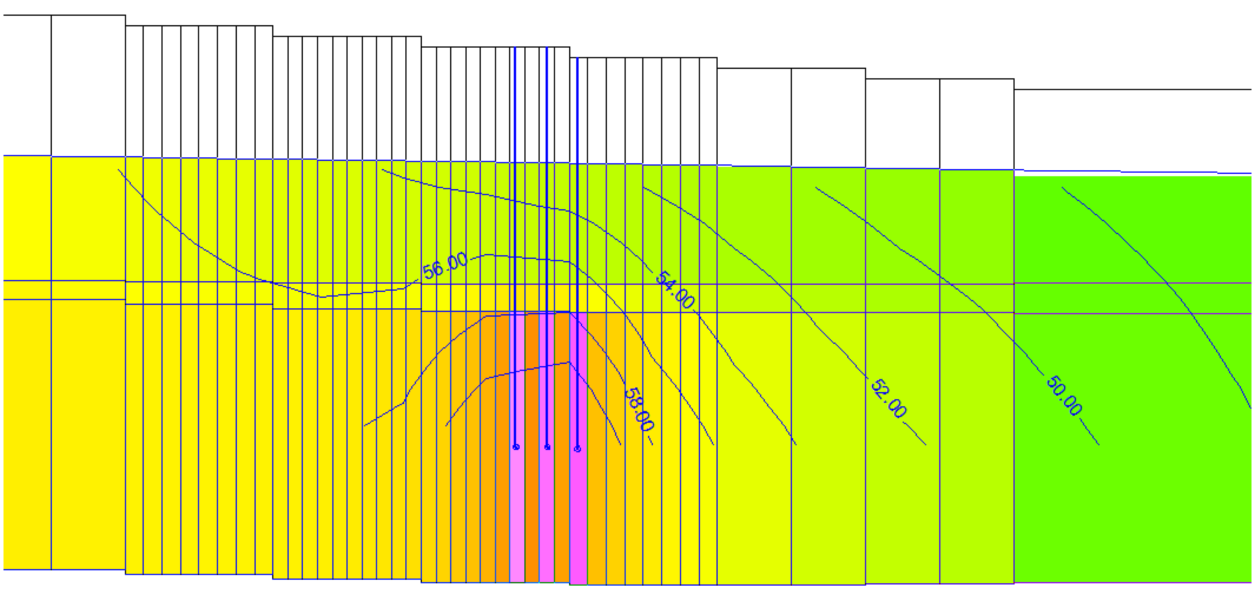

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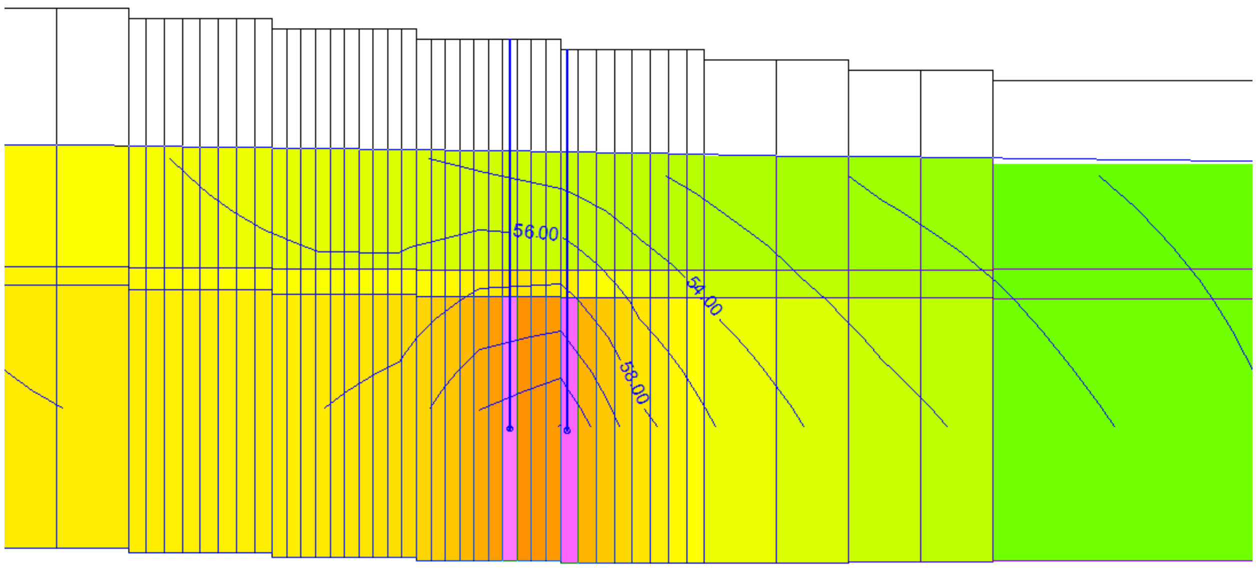

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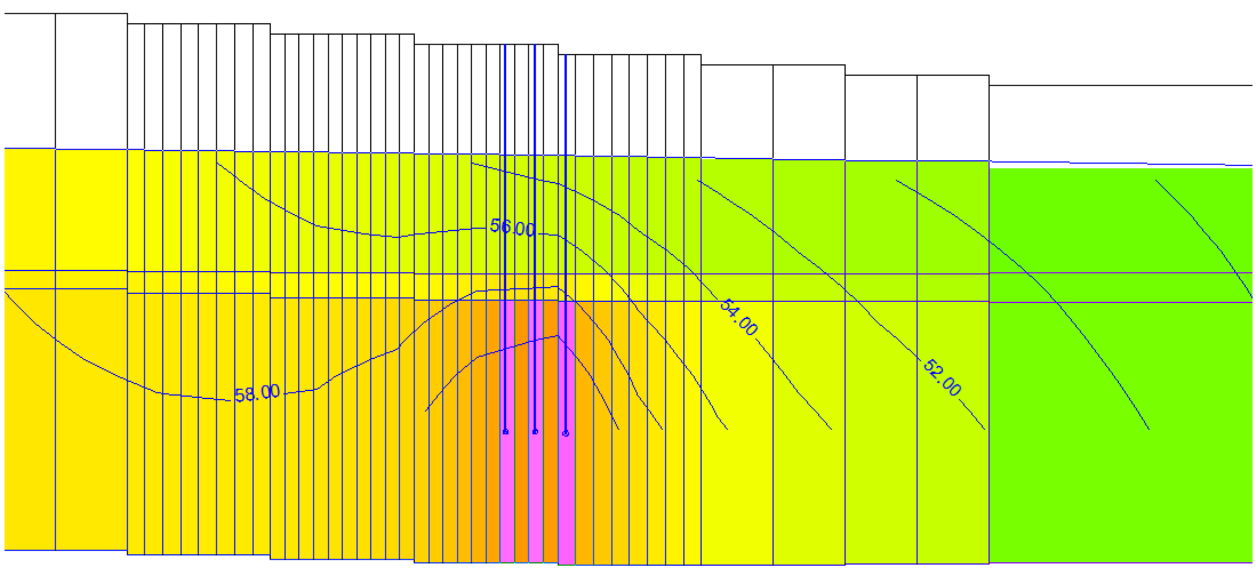

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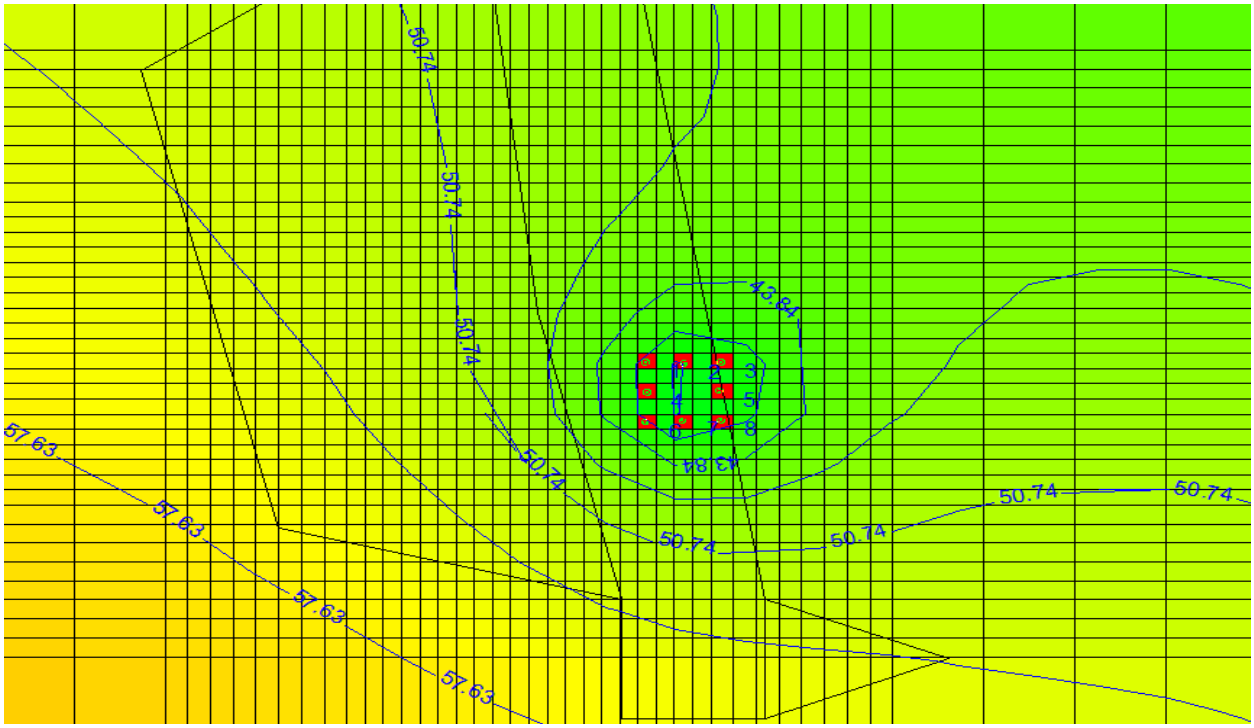
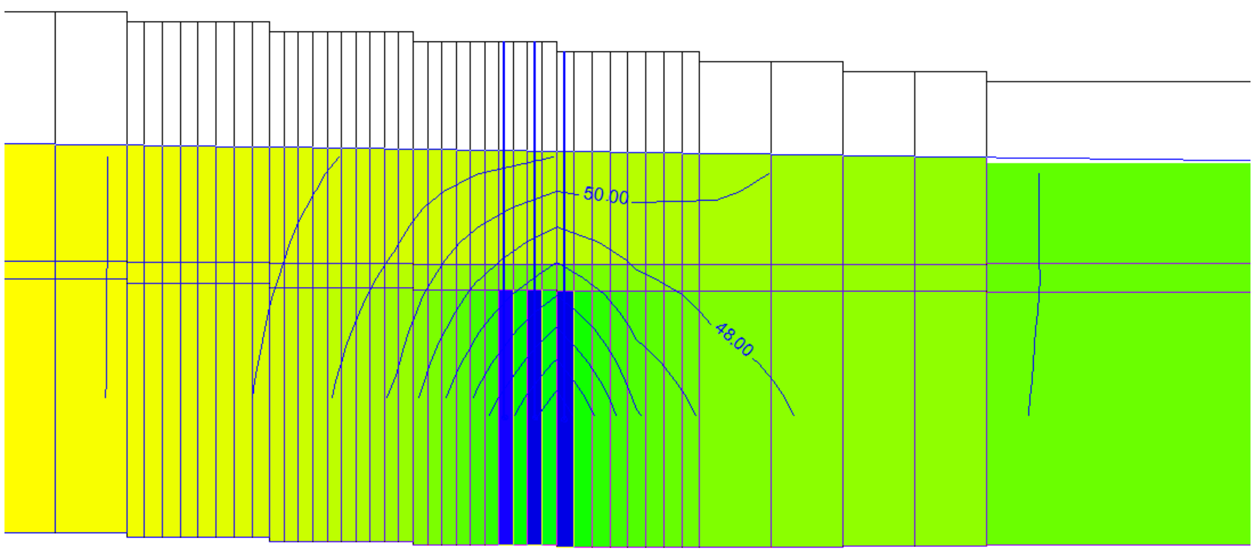


Cross-Section along Row 24



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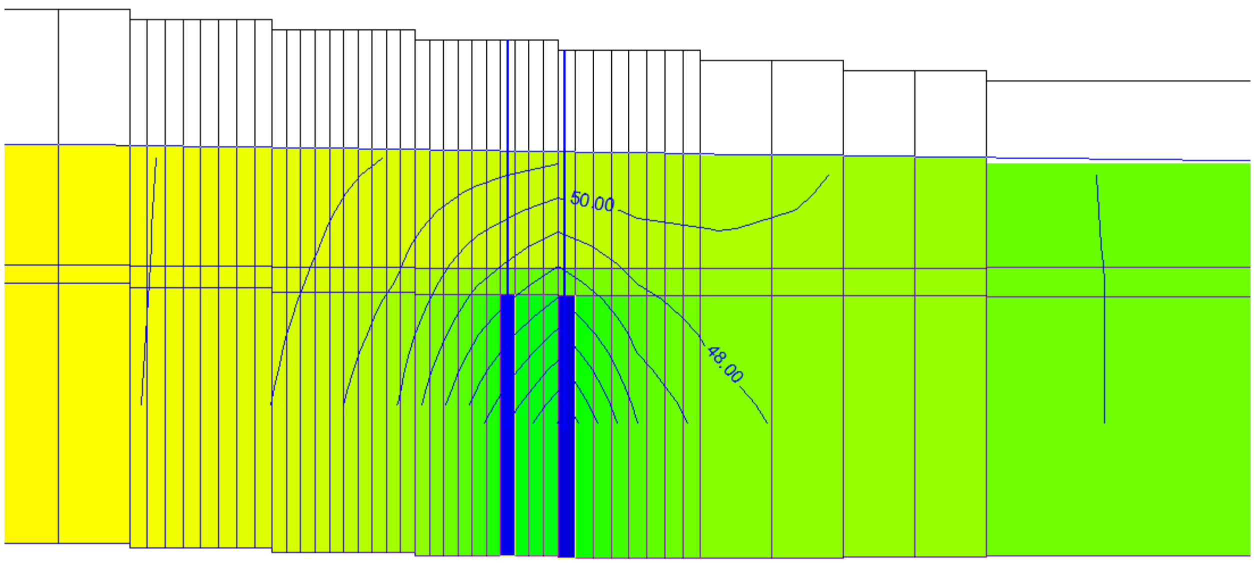
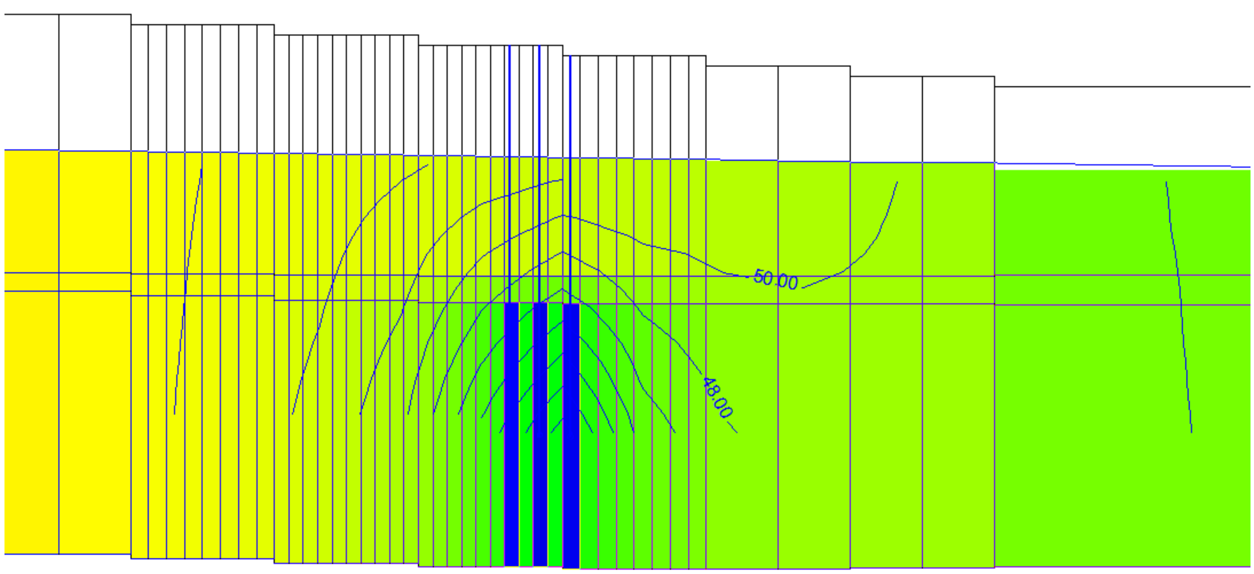


Cross-Section along Row 28



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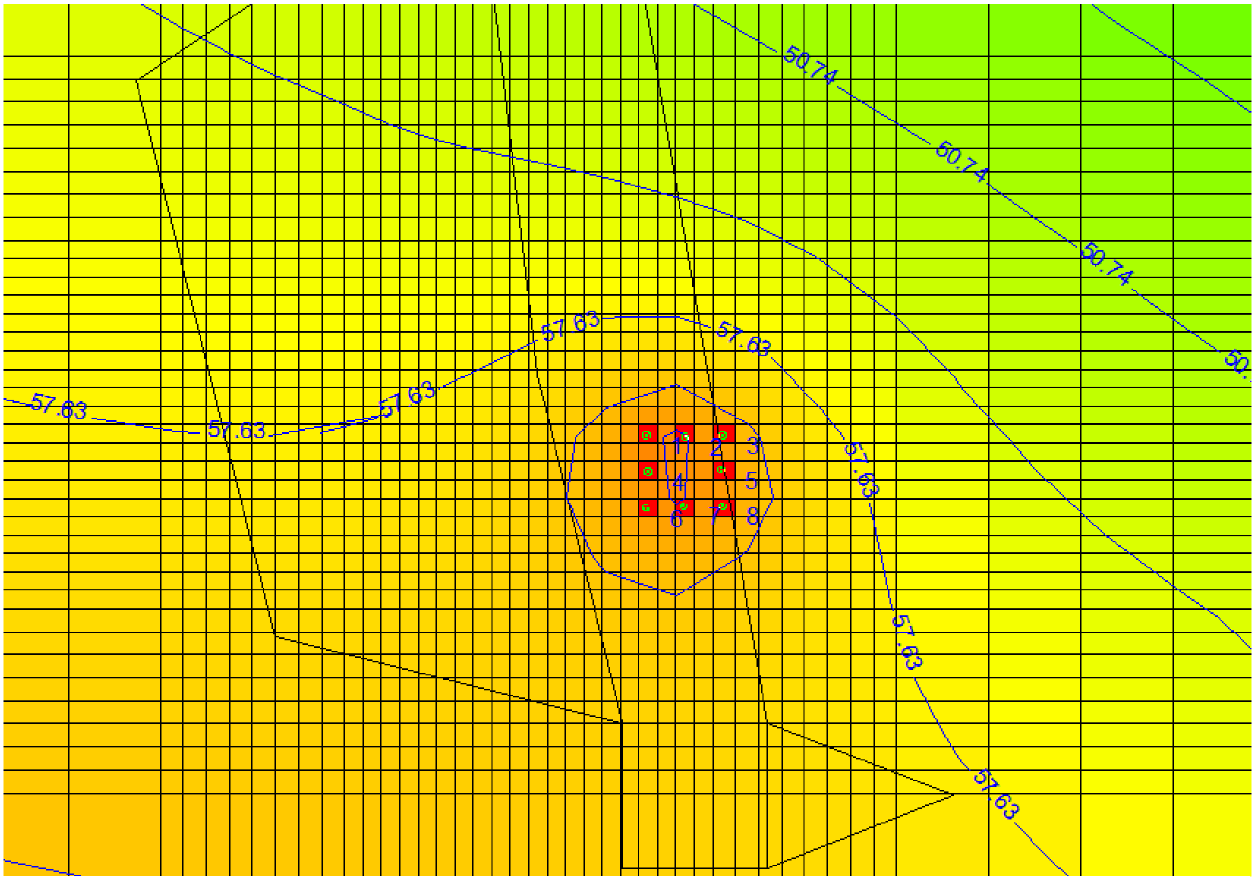
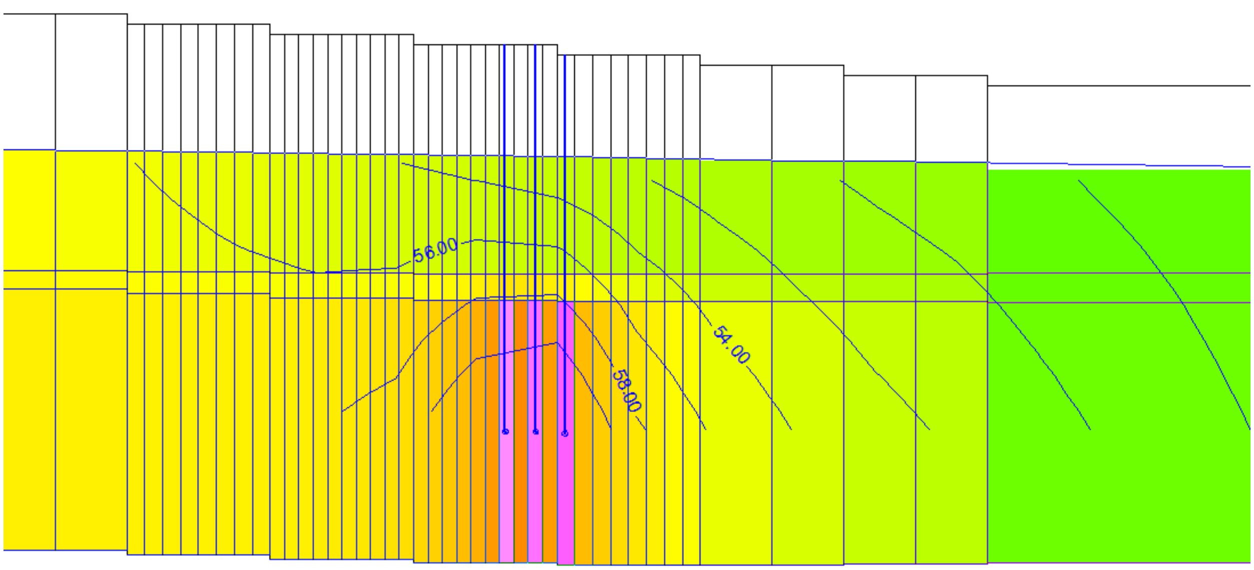
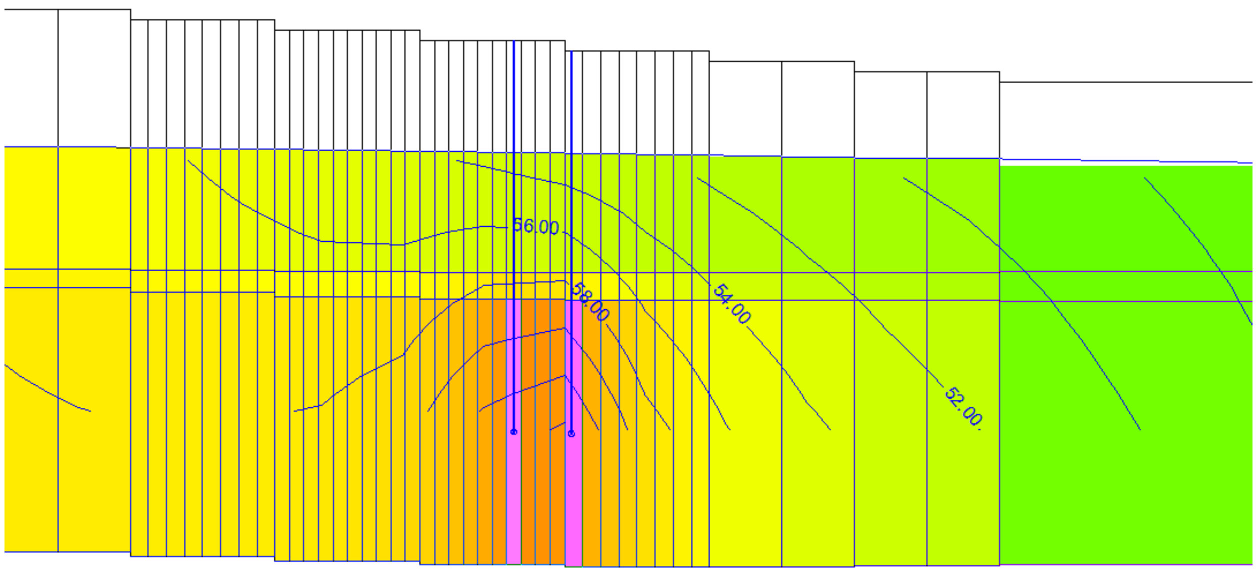


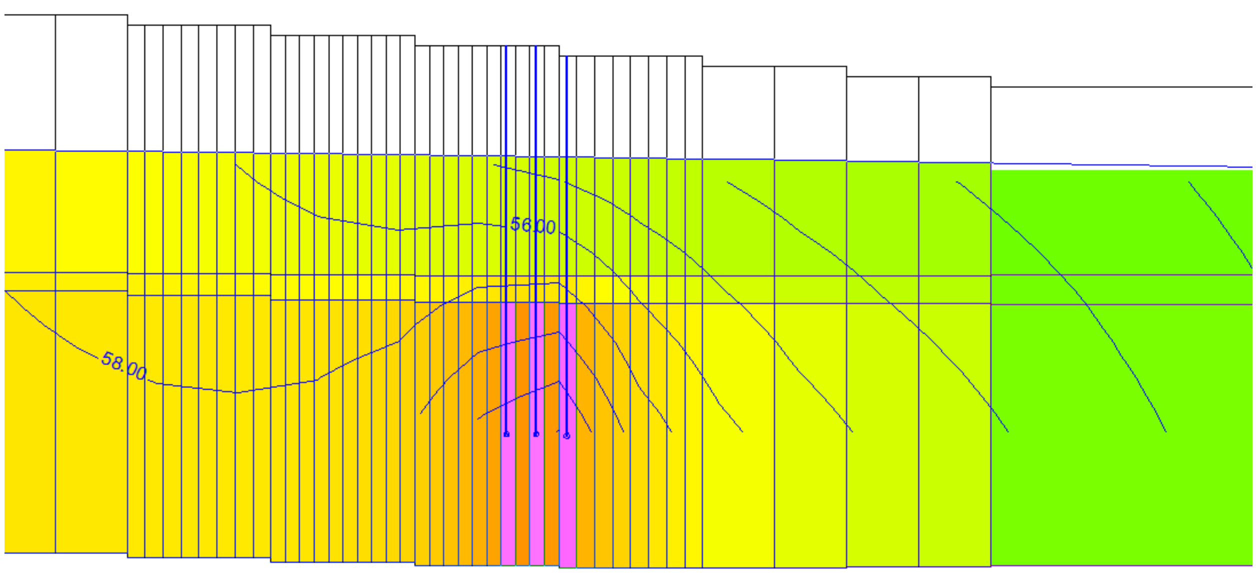
Cross-Section along Row 24



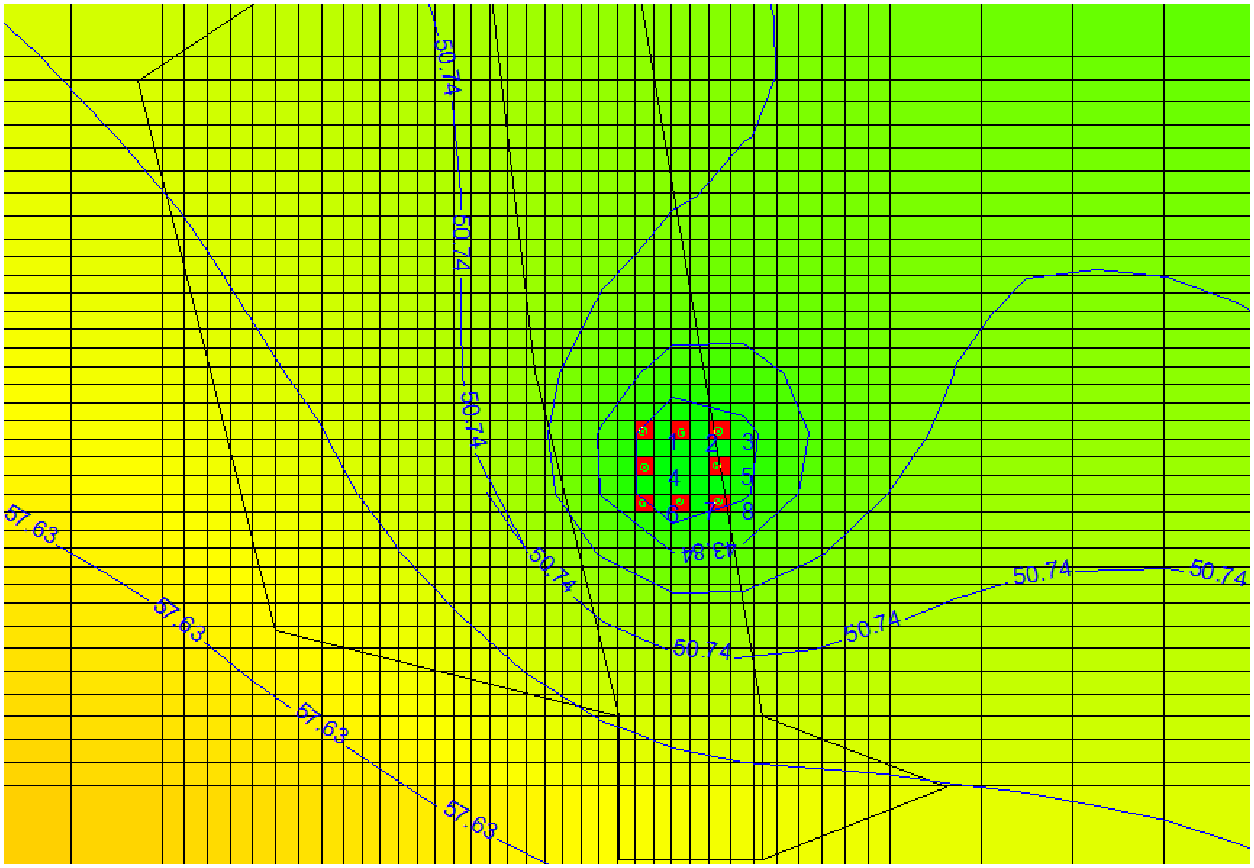
Cross-Section along Row 26



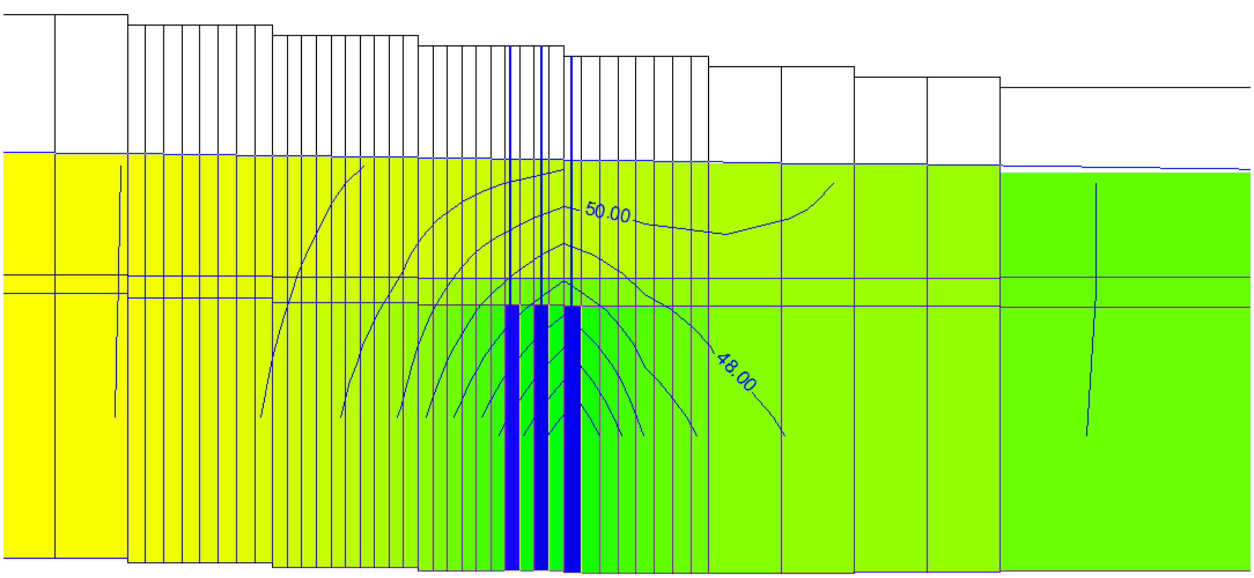
Cross-Section along Row 28



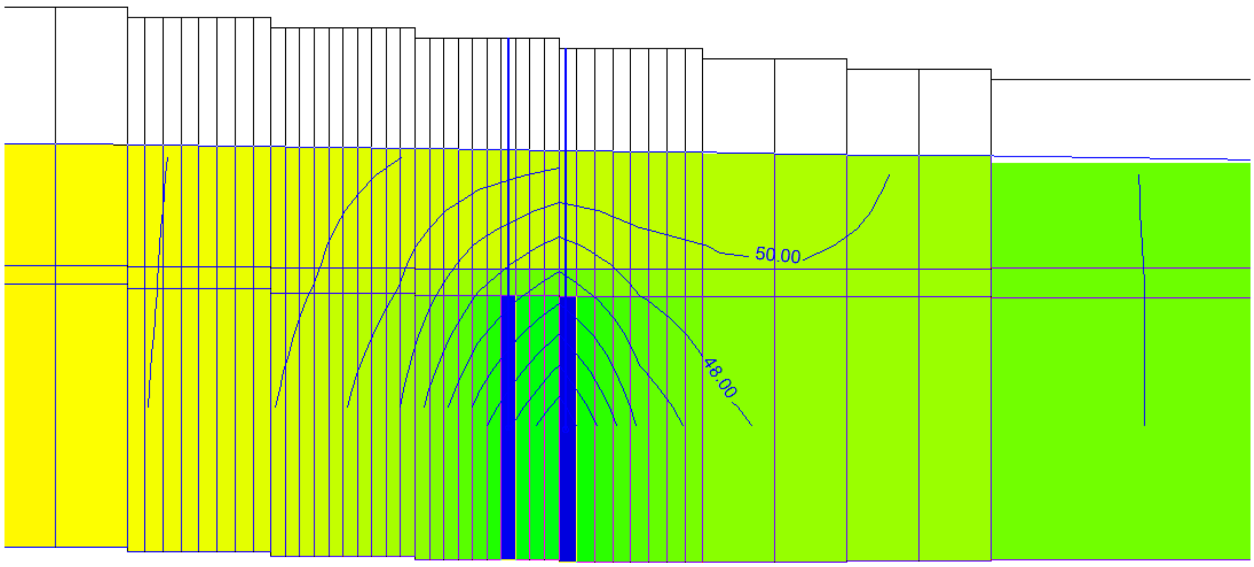
12



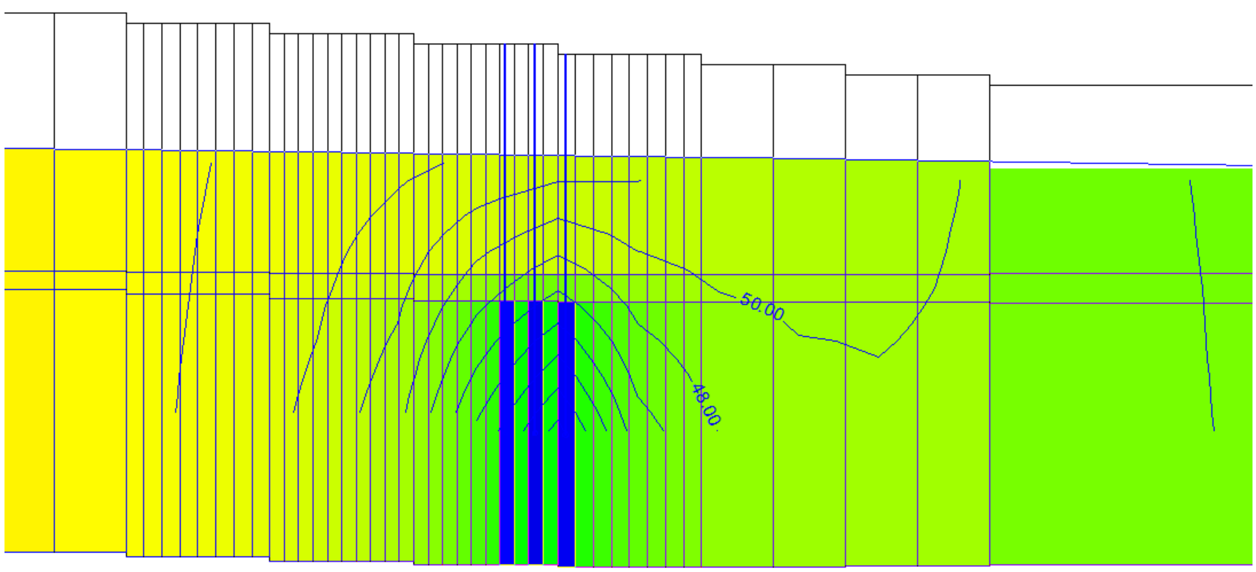
Cross-Section along Row 24



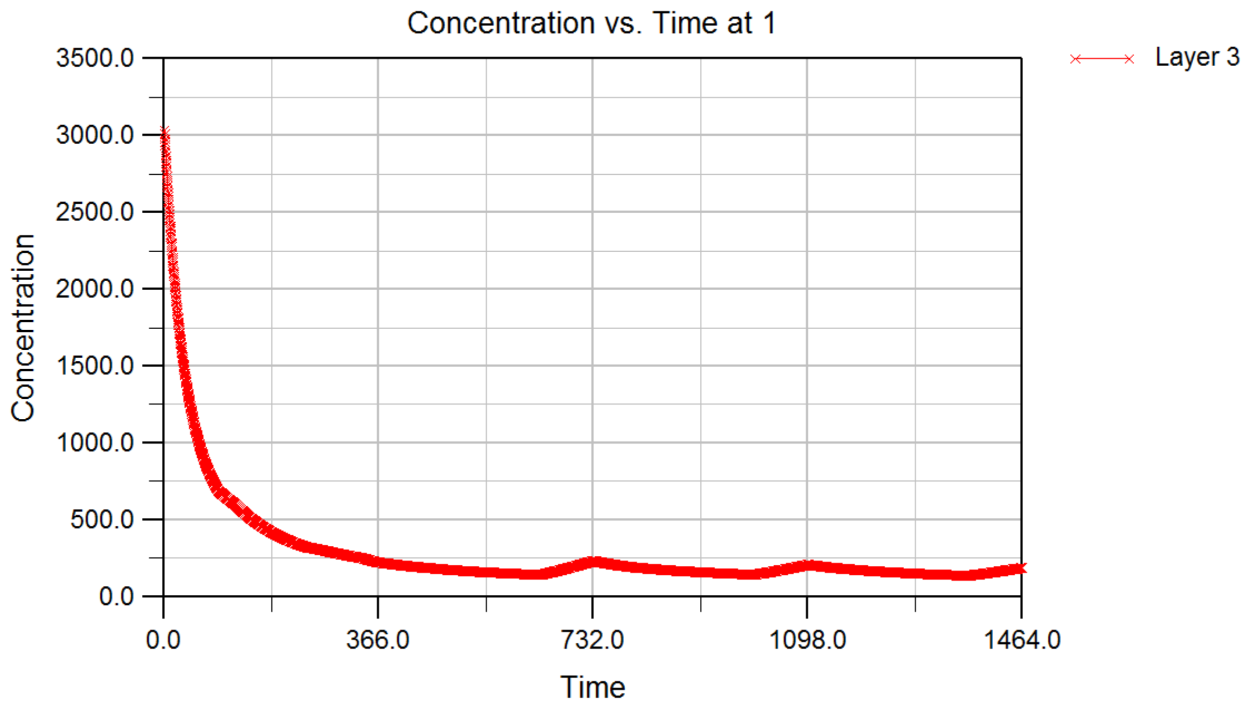
Cross-Section along Row 26



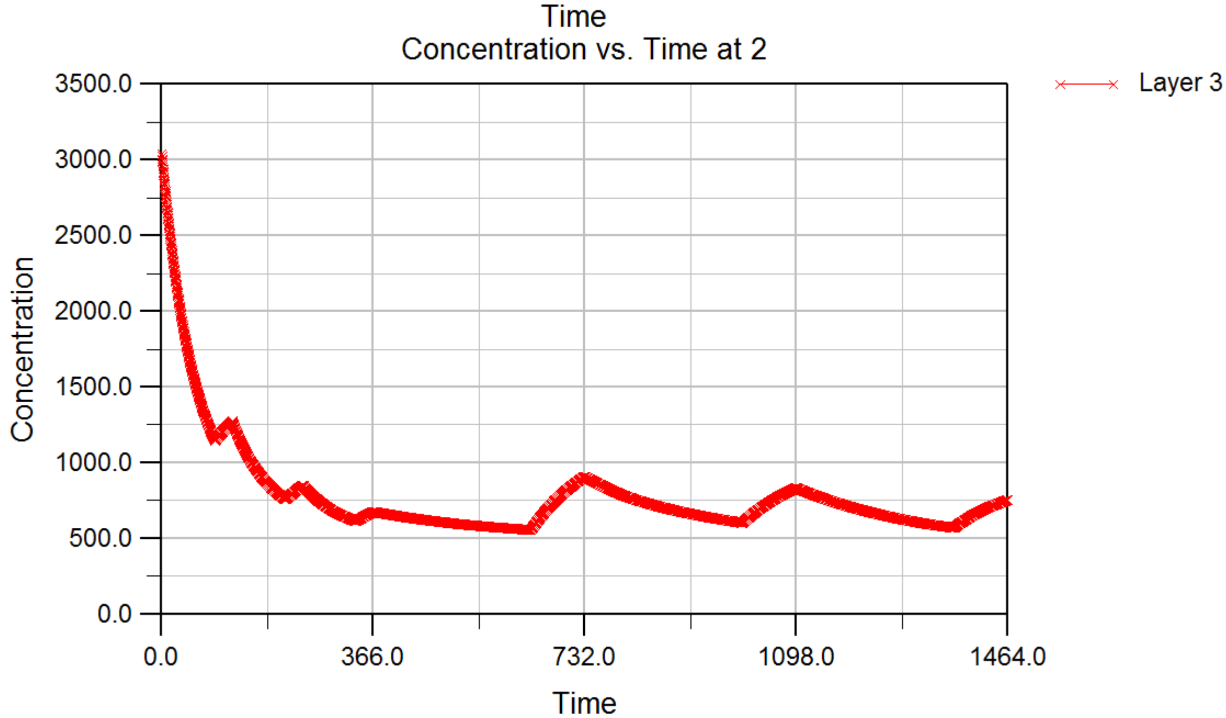
Cross-Section along Row 28



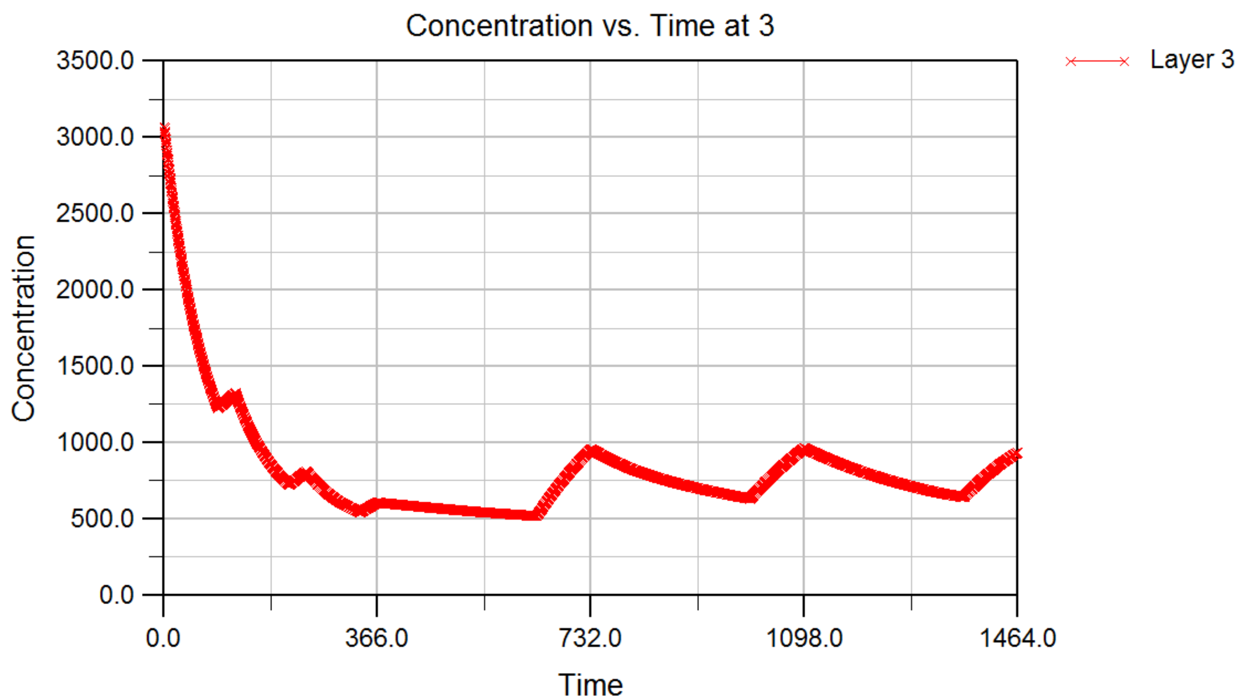
RUN 2 MT3D

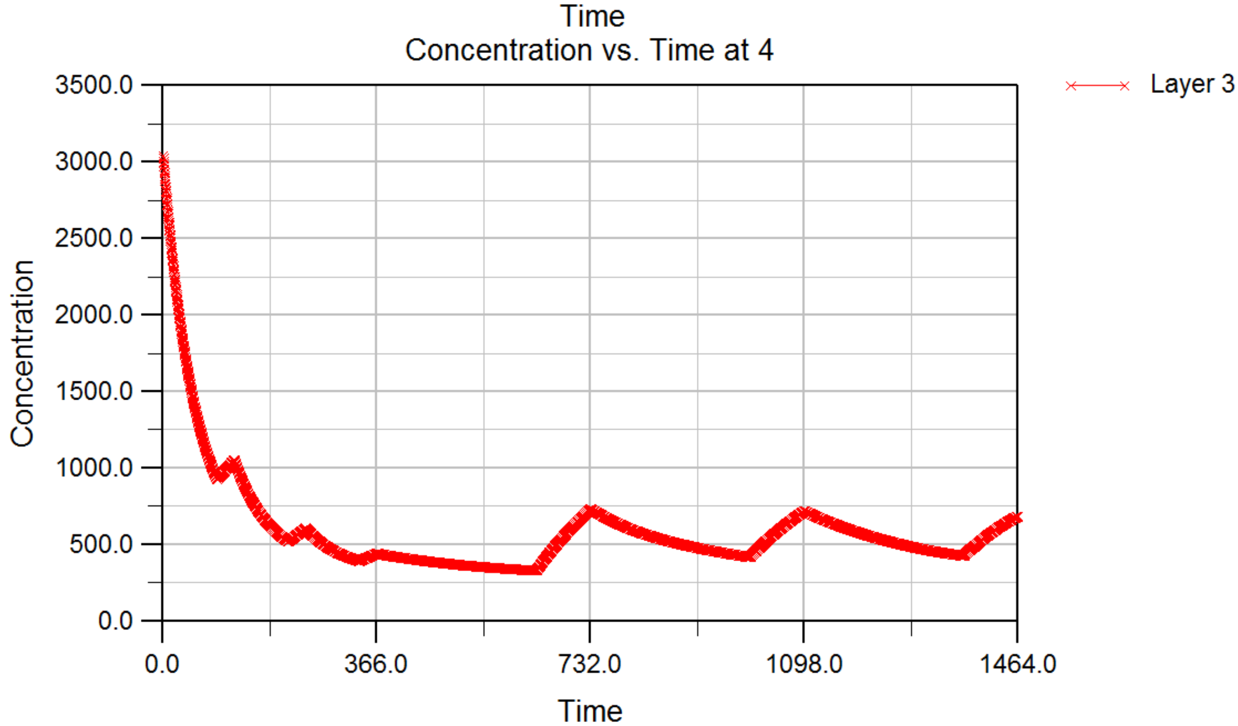


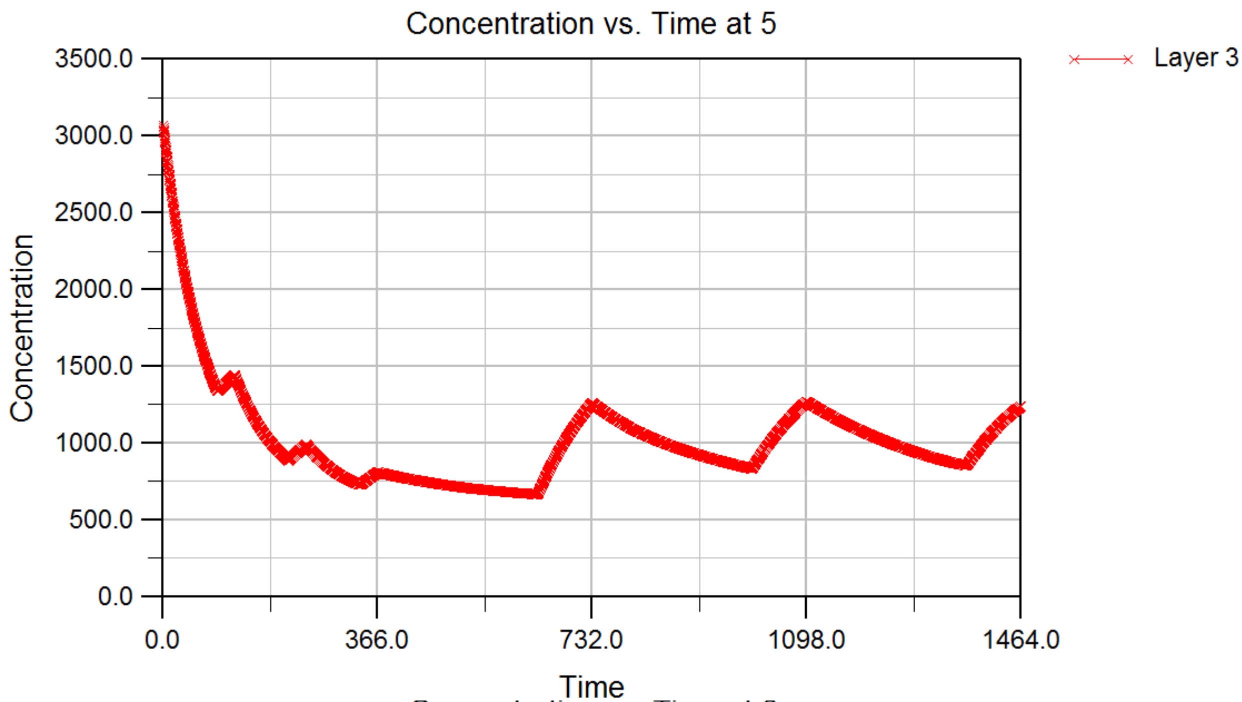
Concentration vs. Time at 1
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time



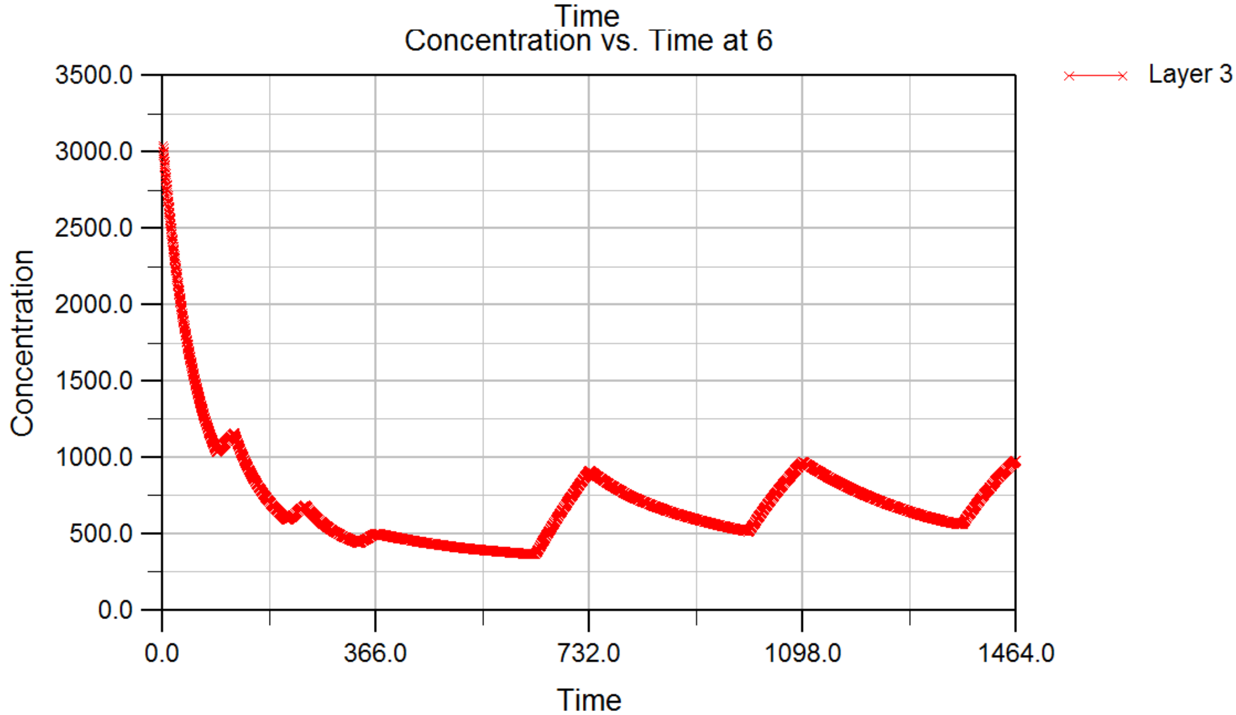
Concentration vs. Time at 2
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time


Concentration vs. Time at 3
Layer 3
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
Concentration
0.0
366.0
732.0
1098.0
1464.0
Time

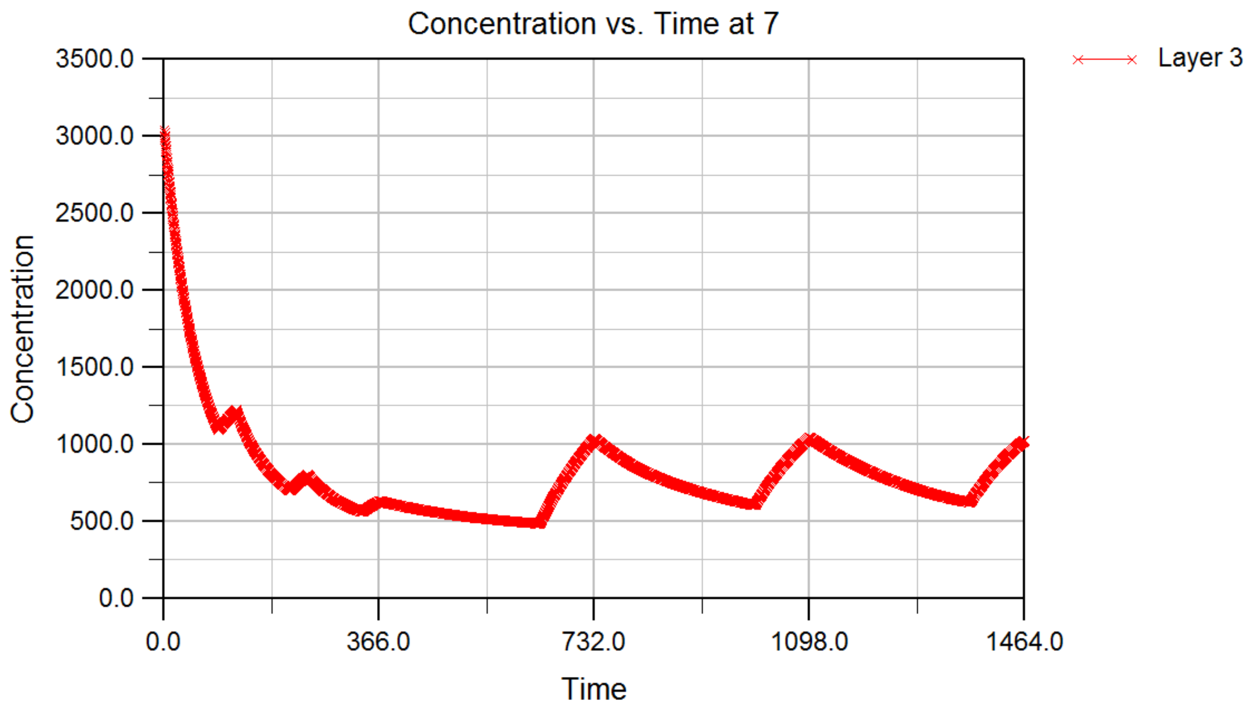

Concentration vs. Time at 4
Layer 3
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
Concentration
0.0
366.0
732.0
1098.0
1464.0
Time



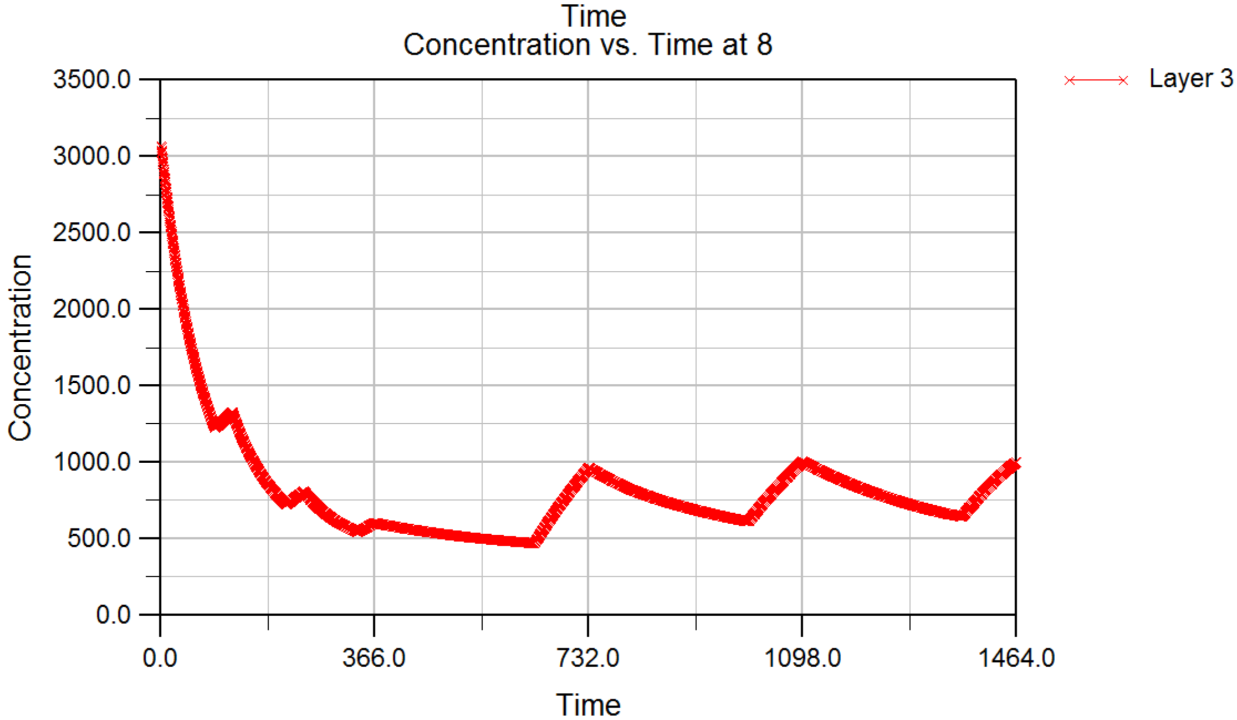
Concentration vs. Time at 5
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time



Concentration vs. Time at 6
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time

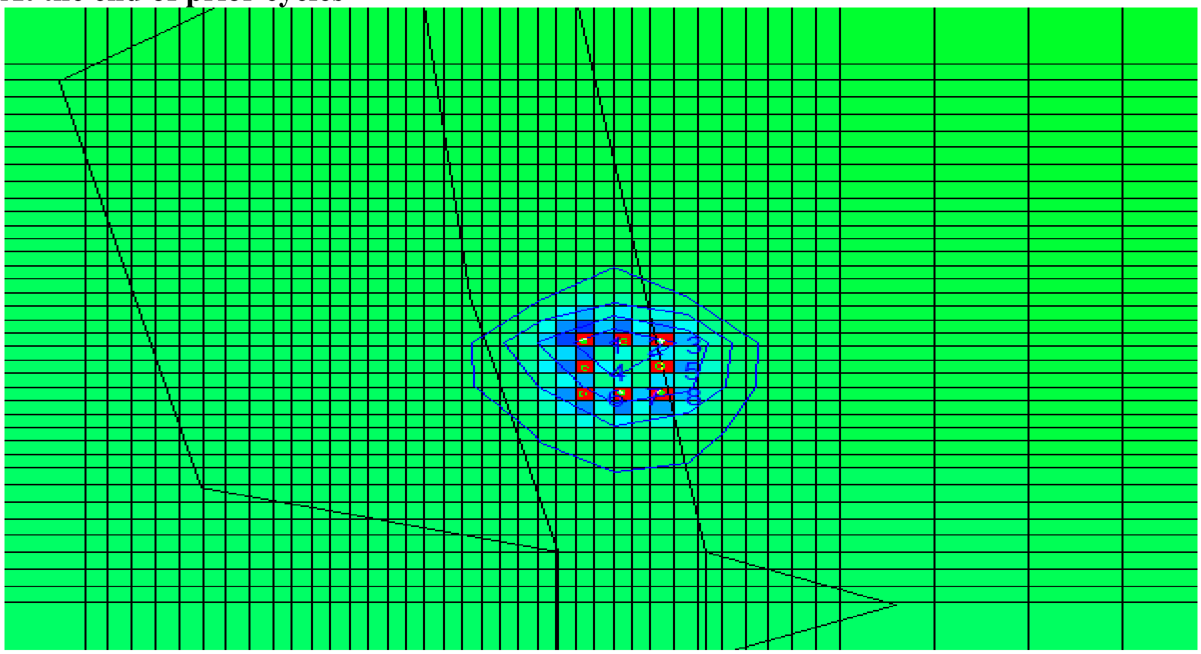


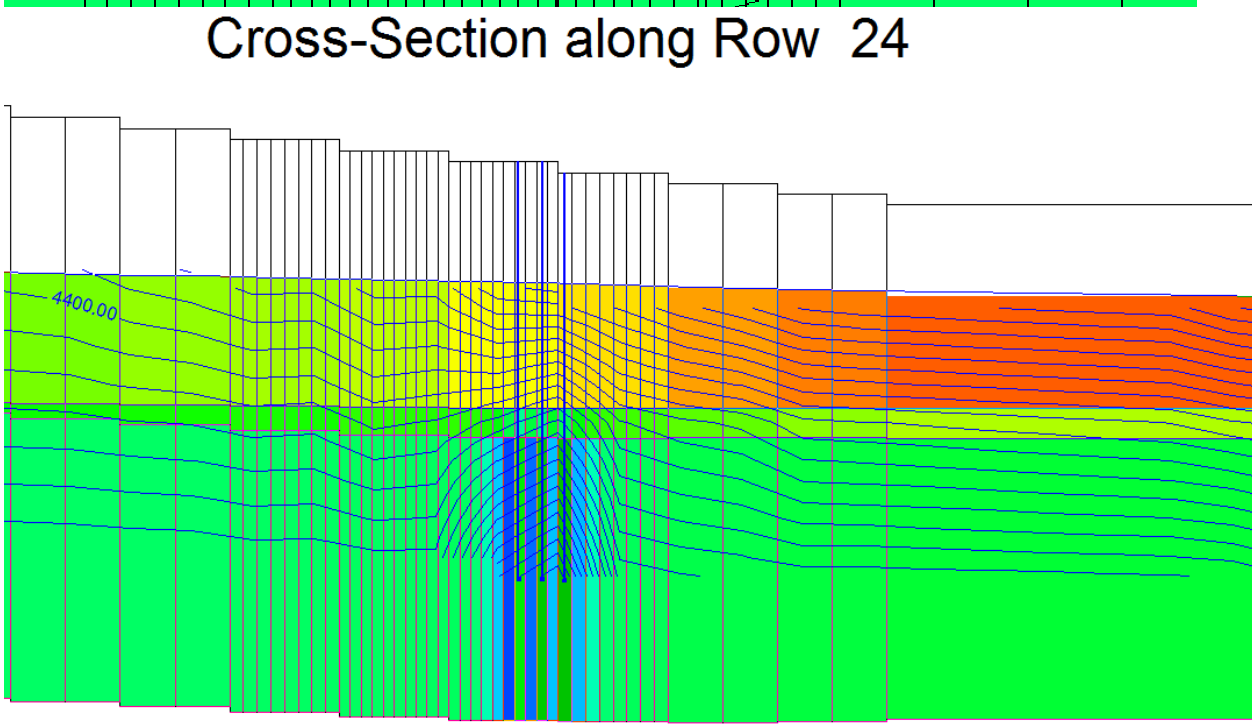
Concentration vs. Time at 7
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time



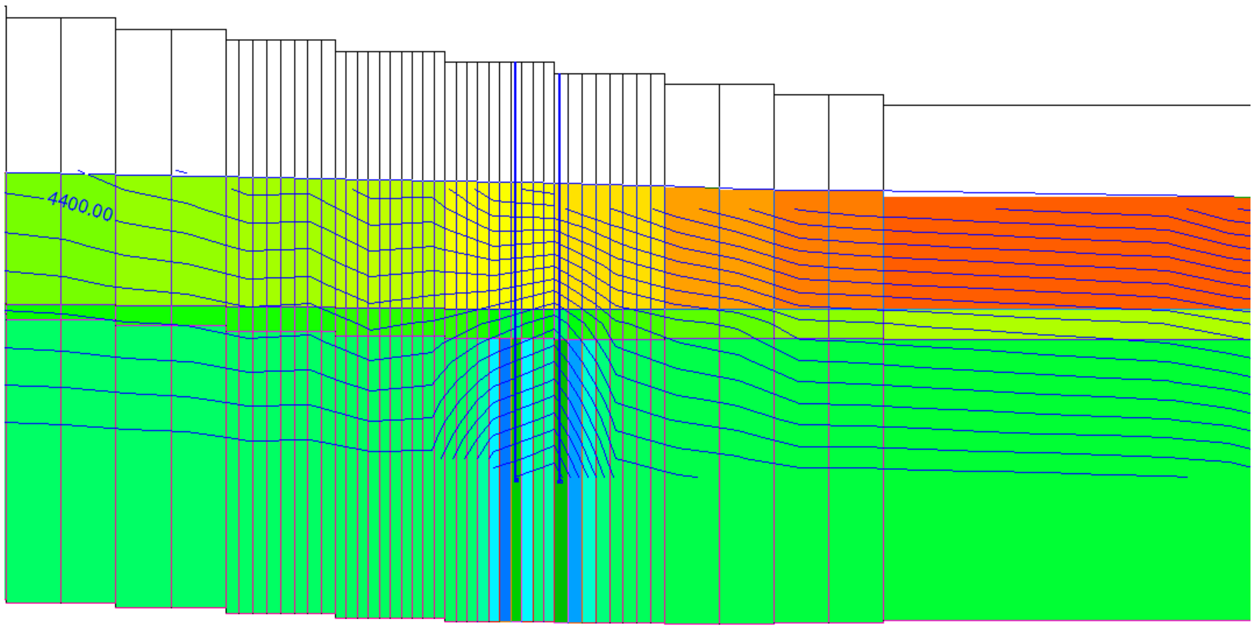
Concentration vs. Time at 8
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time

At the end of prior cycles

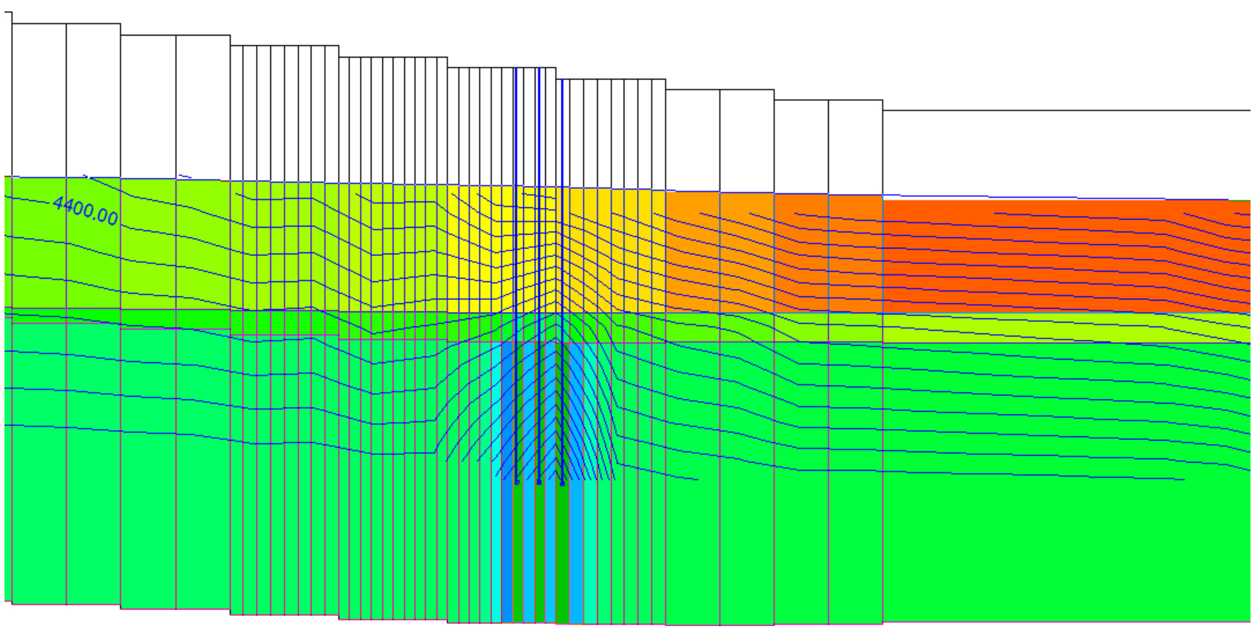




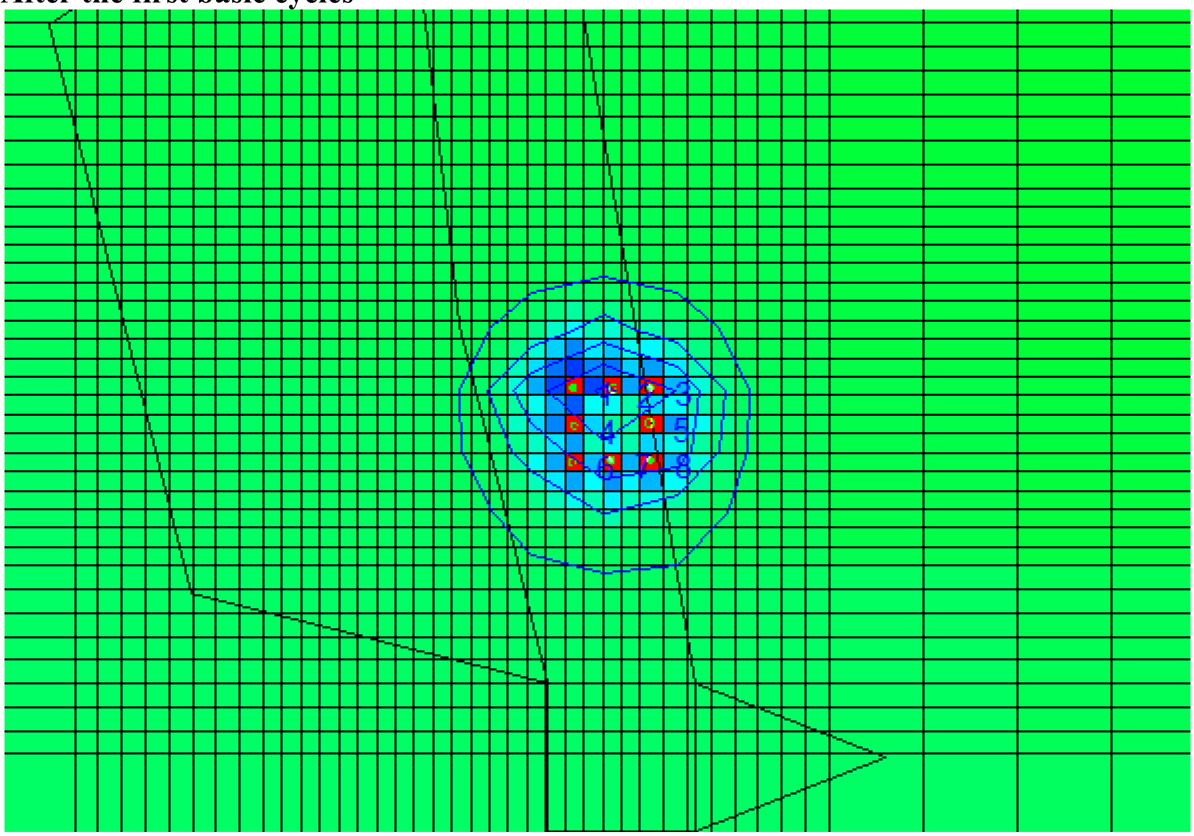
Cross-Section along Row 26



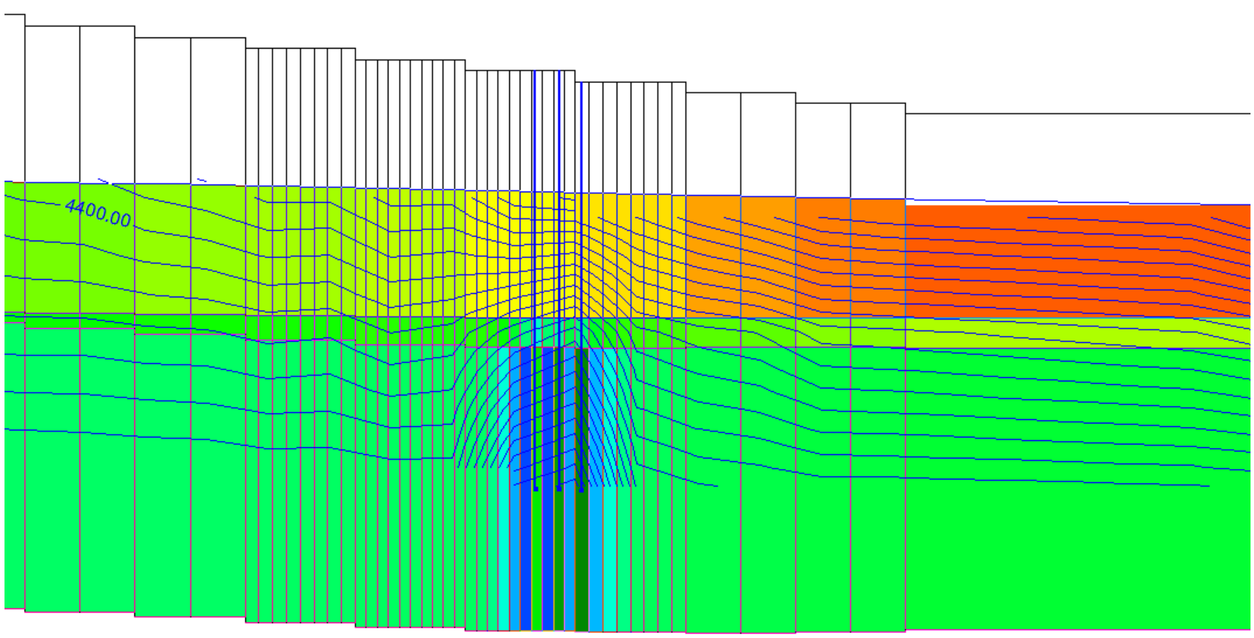
Cross-Section along Row 28



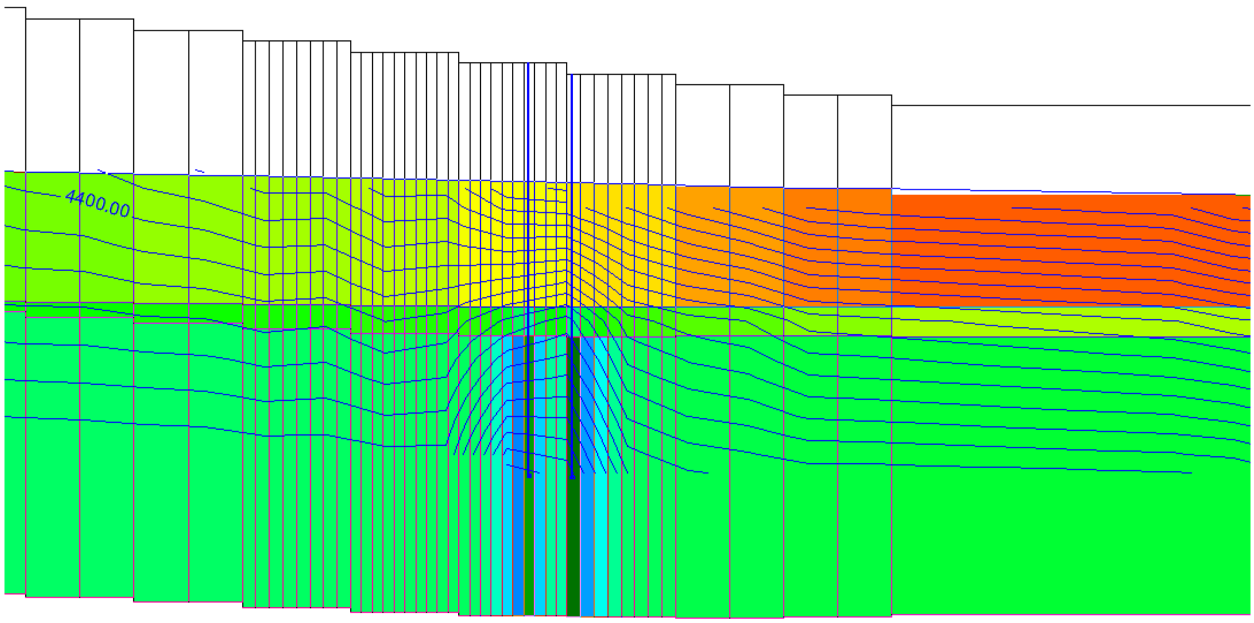
After the first basic cycles



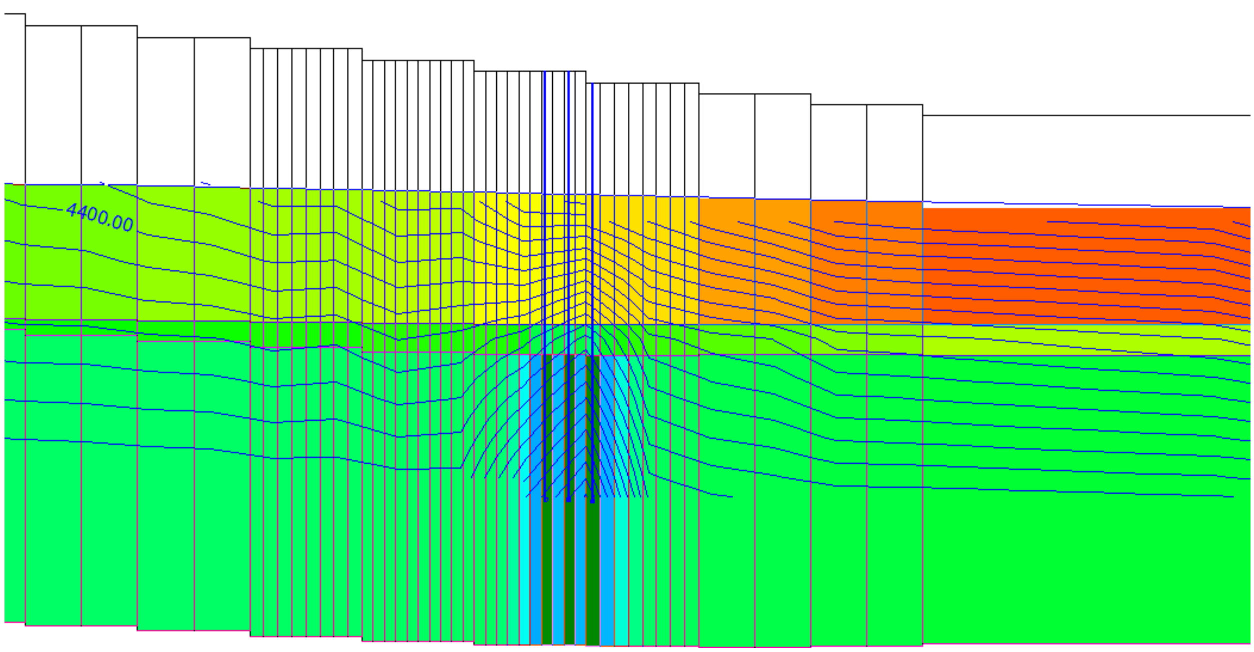
Cross-Section along Row 24



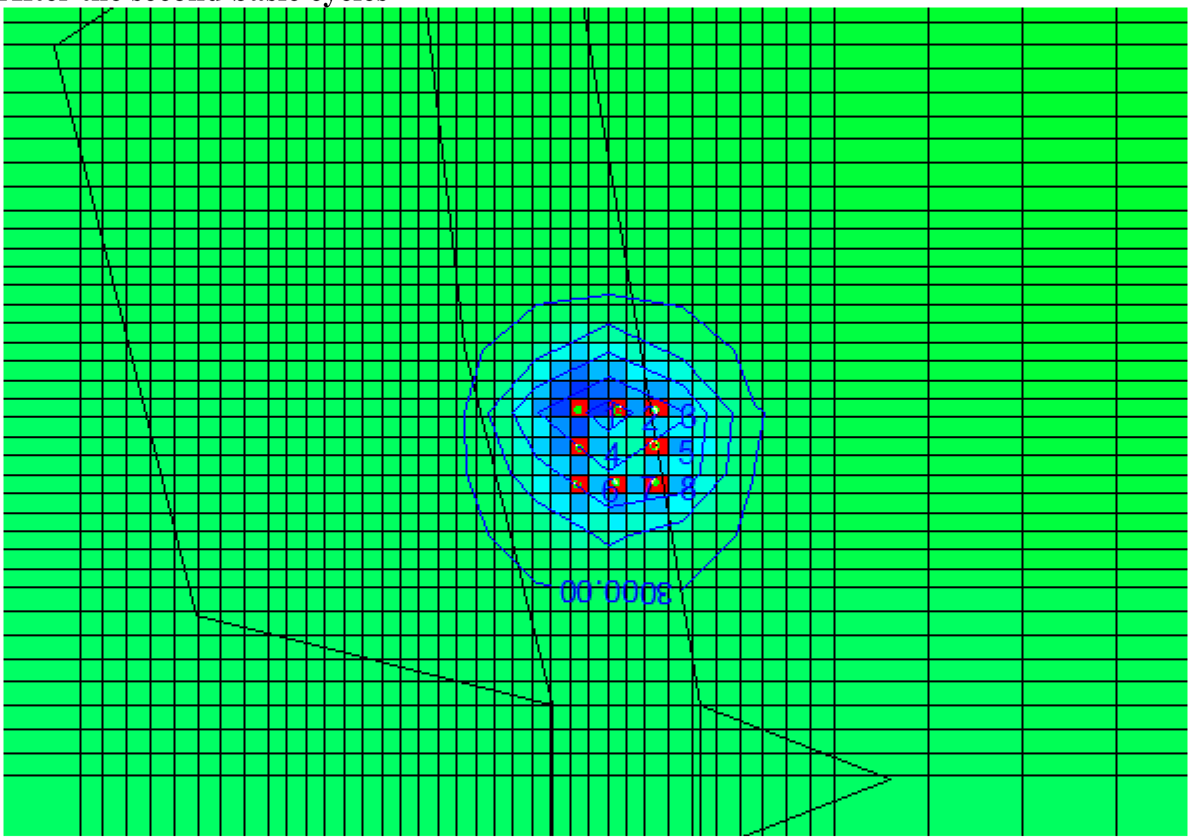
Cross-Section along Row 26



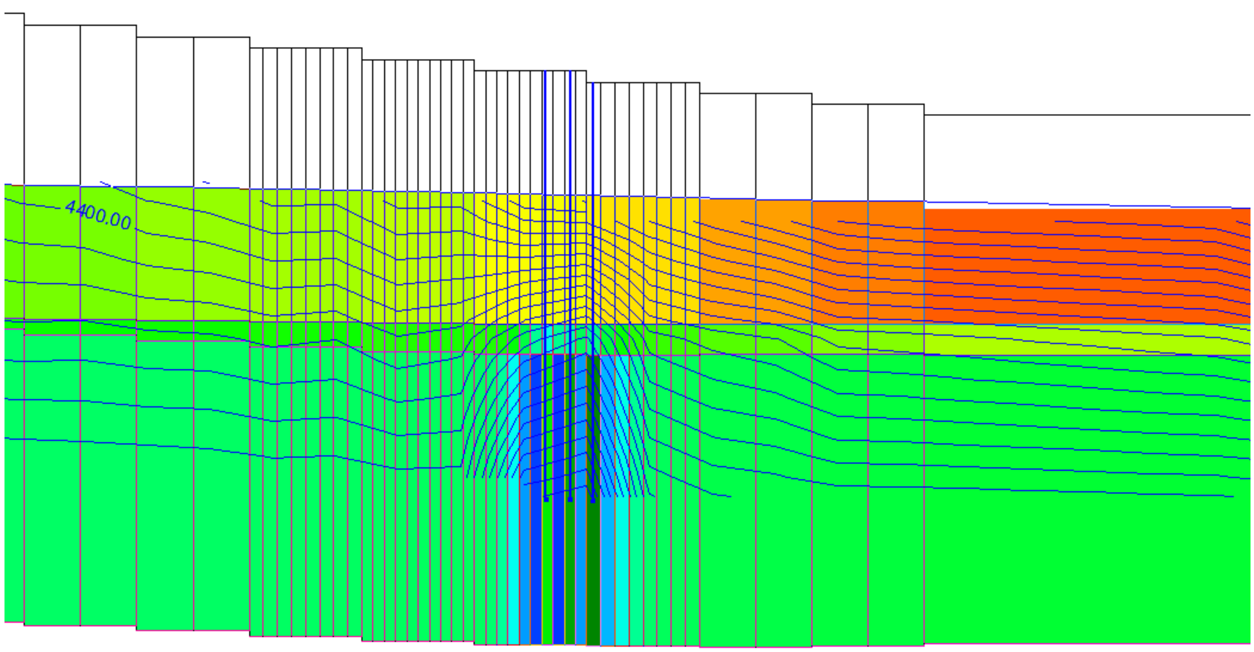
Cross-Section along Row 28



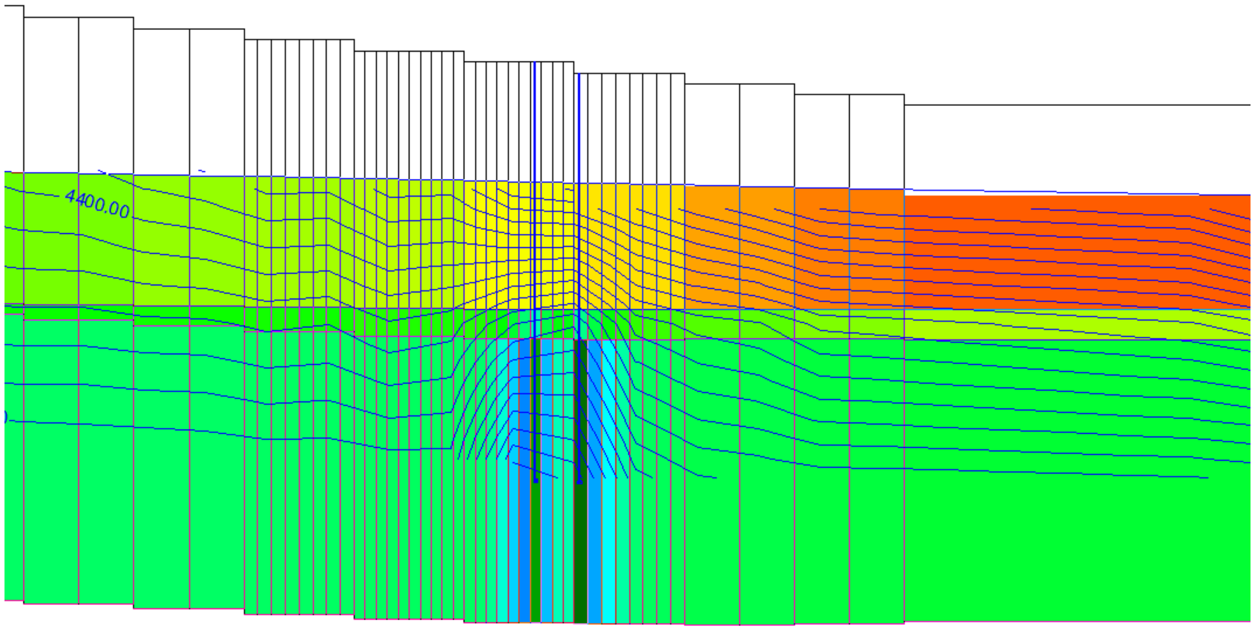
After the second basic cycles



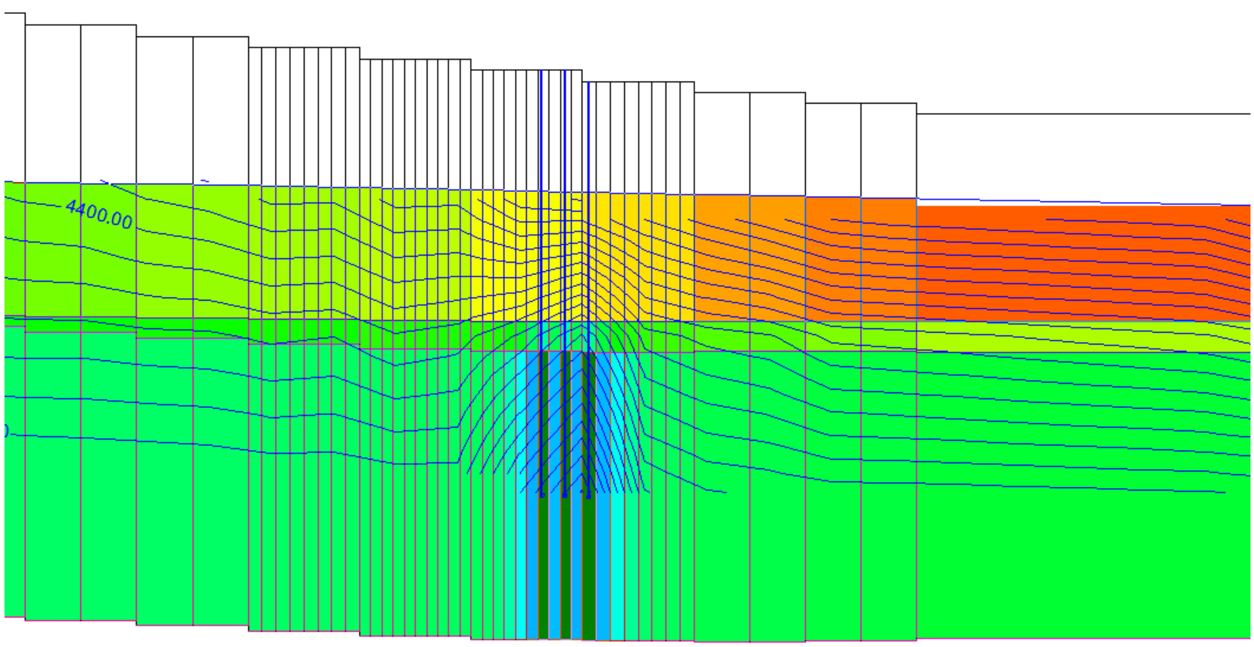
Cross-Section along Row 24



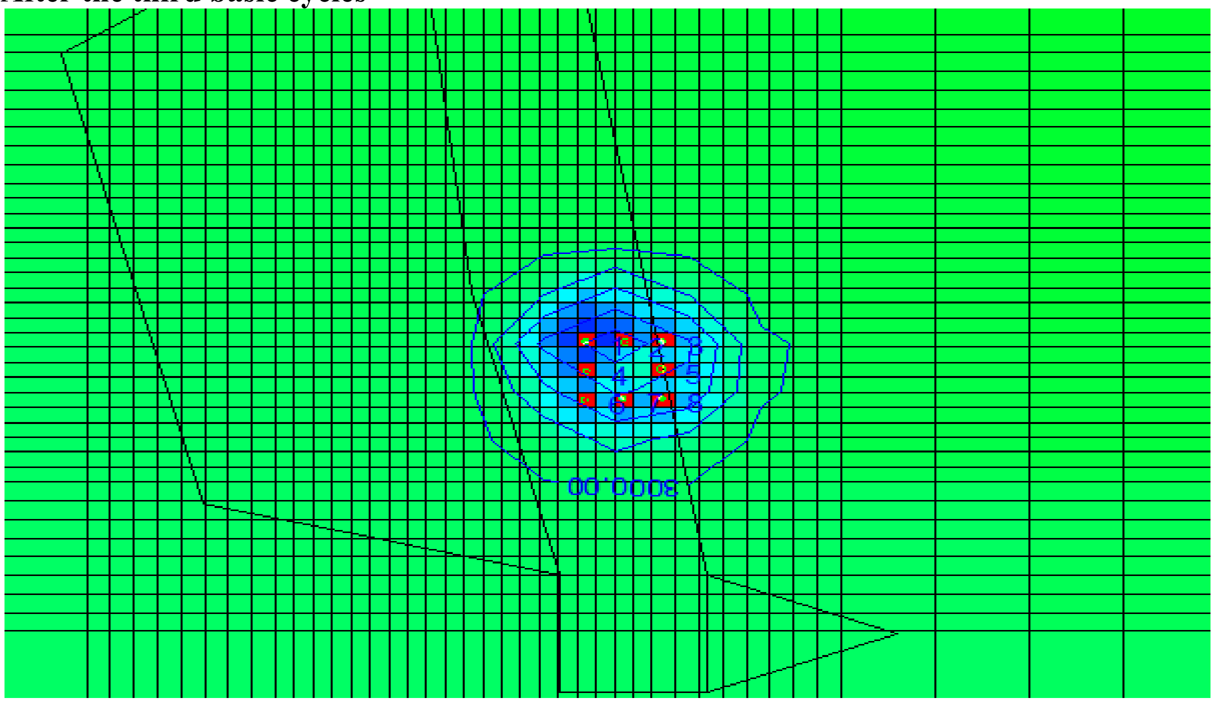
Cross-Section along Row 26



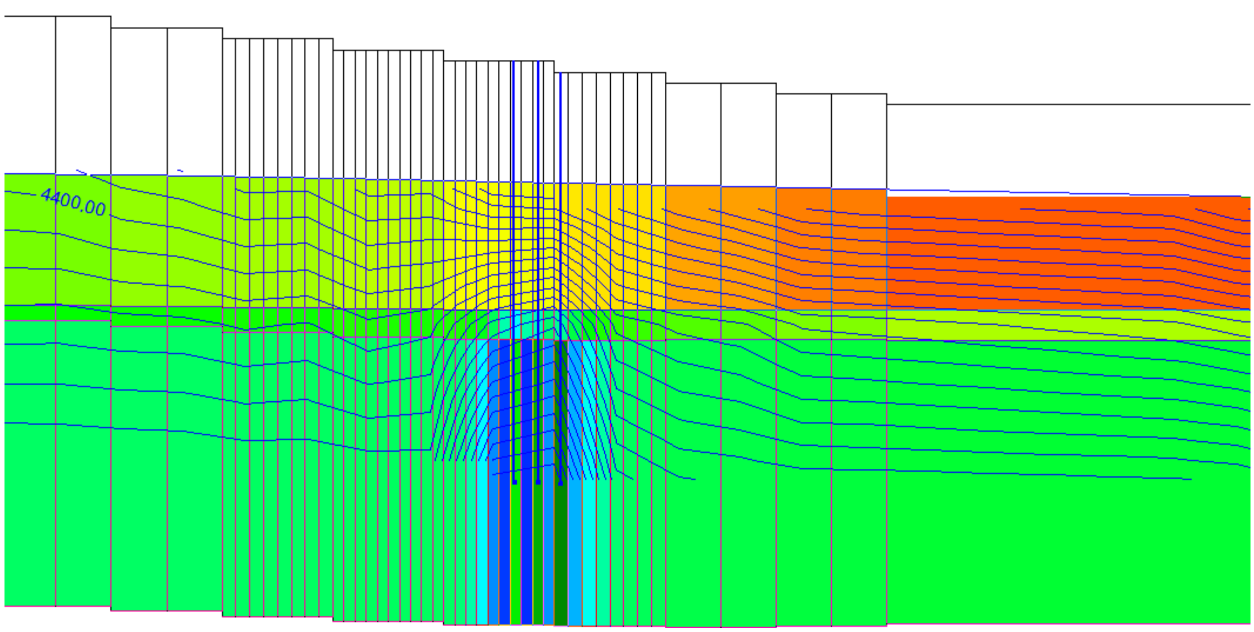
Cross-Section along Row 28



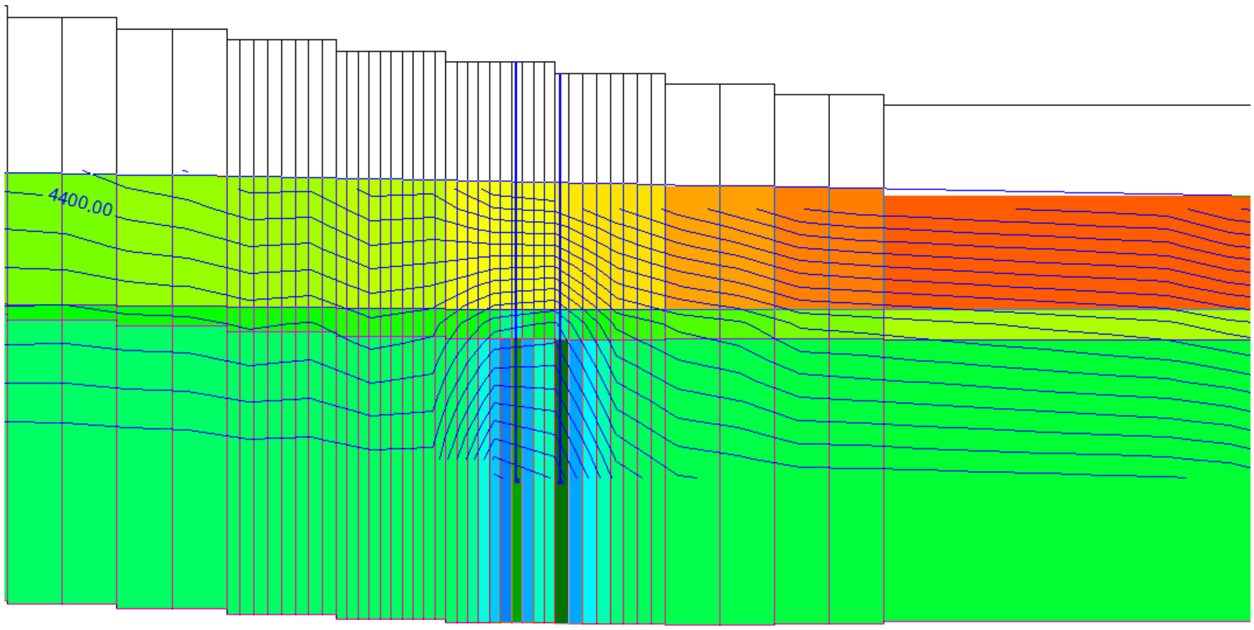
After the third basic cycles



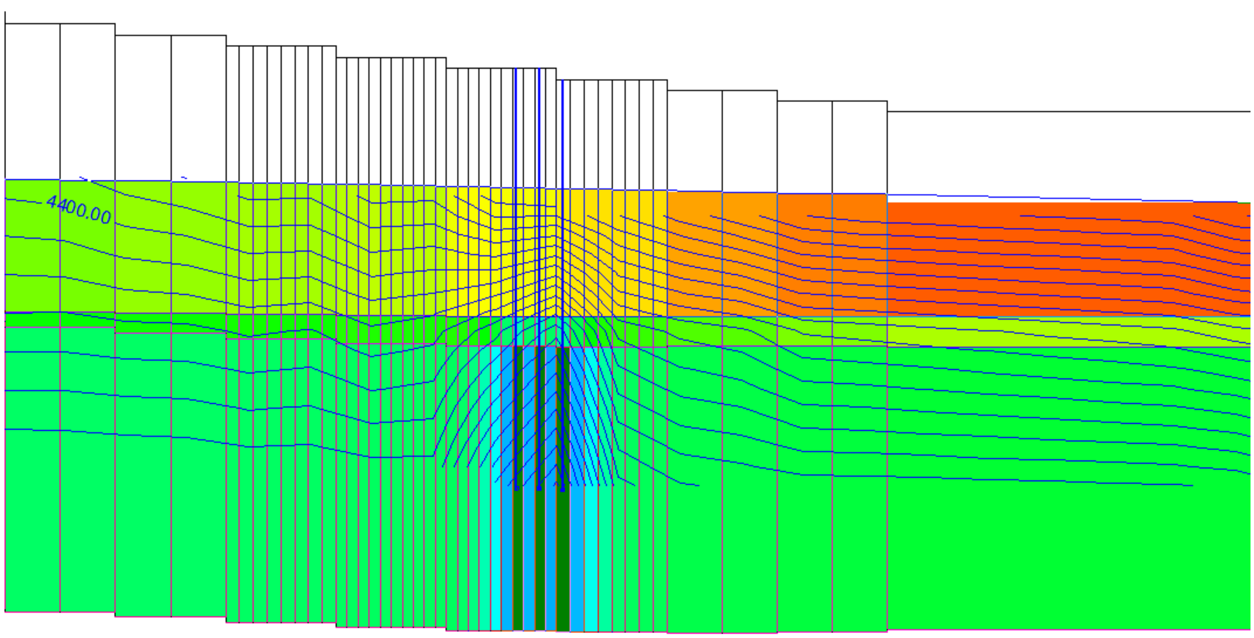
Cross-Section along Row 24



Cross-Section along Row 26

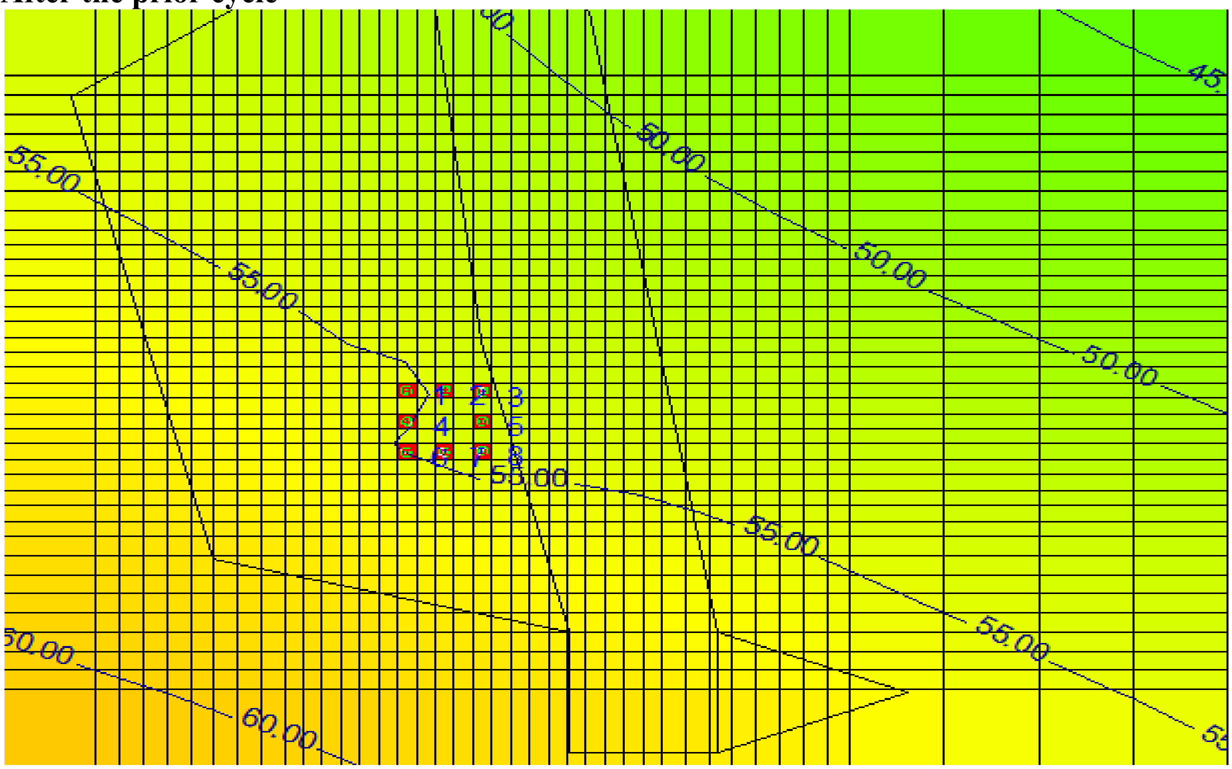


Cross-Section along Row 28

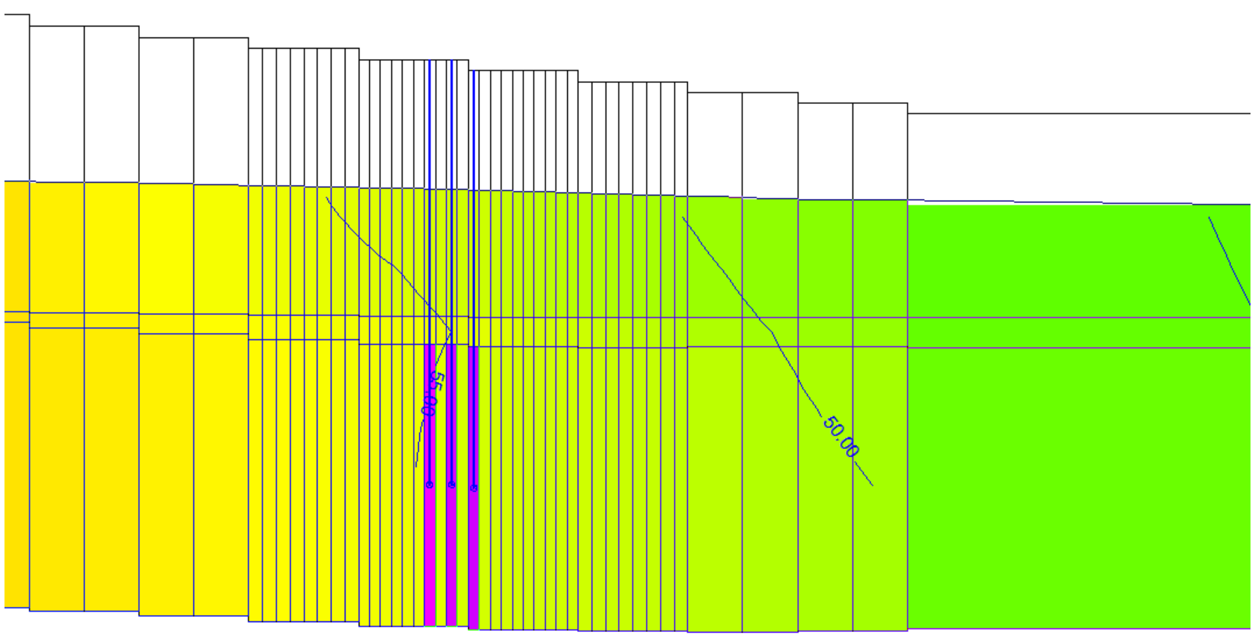


RUN3 MODFLOW

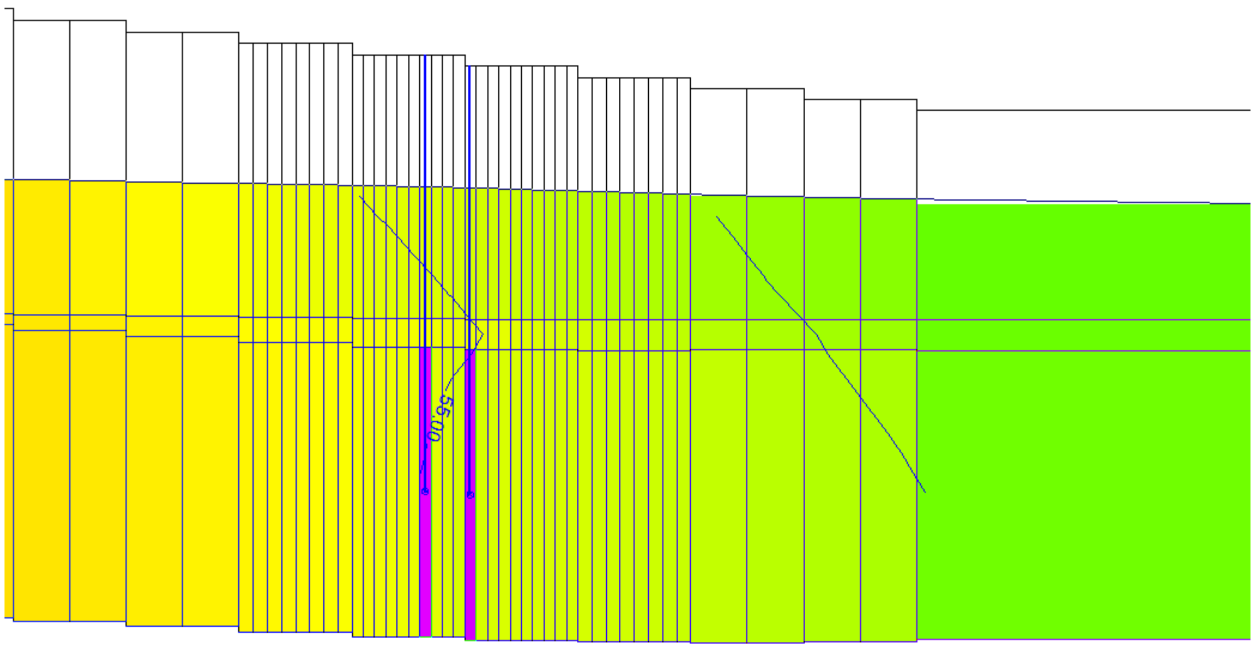
After the prior cycle



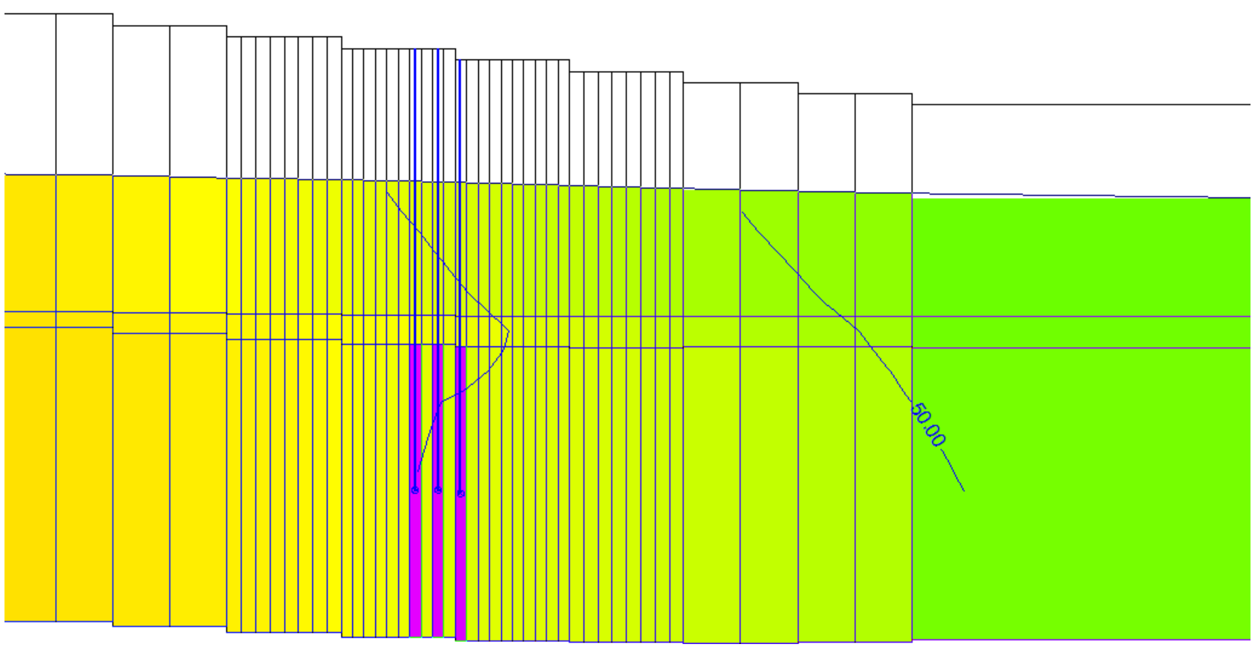
Cross-Section along Row 24



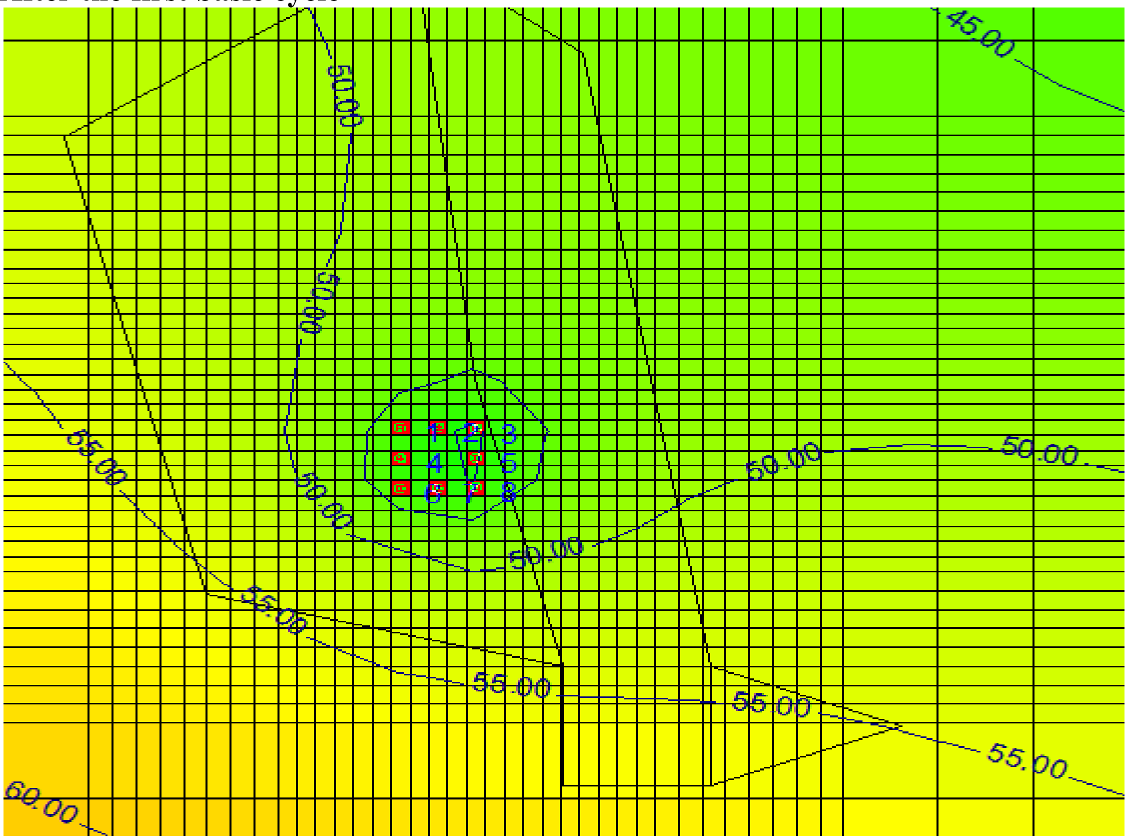
Cross-Section along Row 26



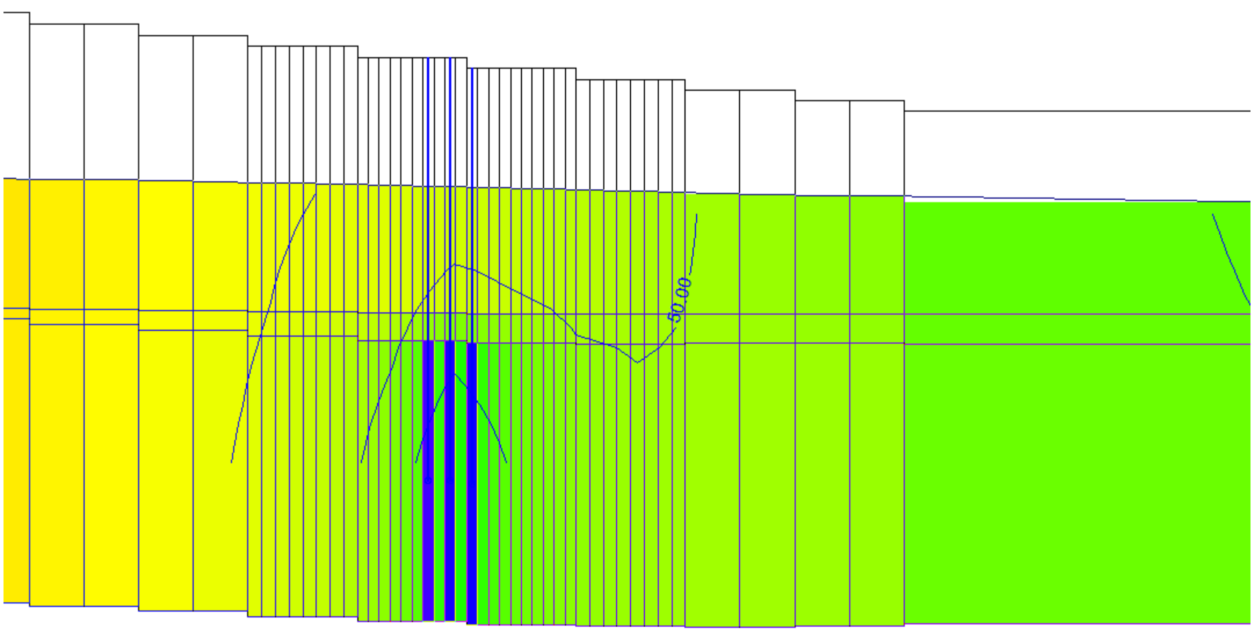
Cross-Section along Row 28



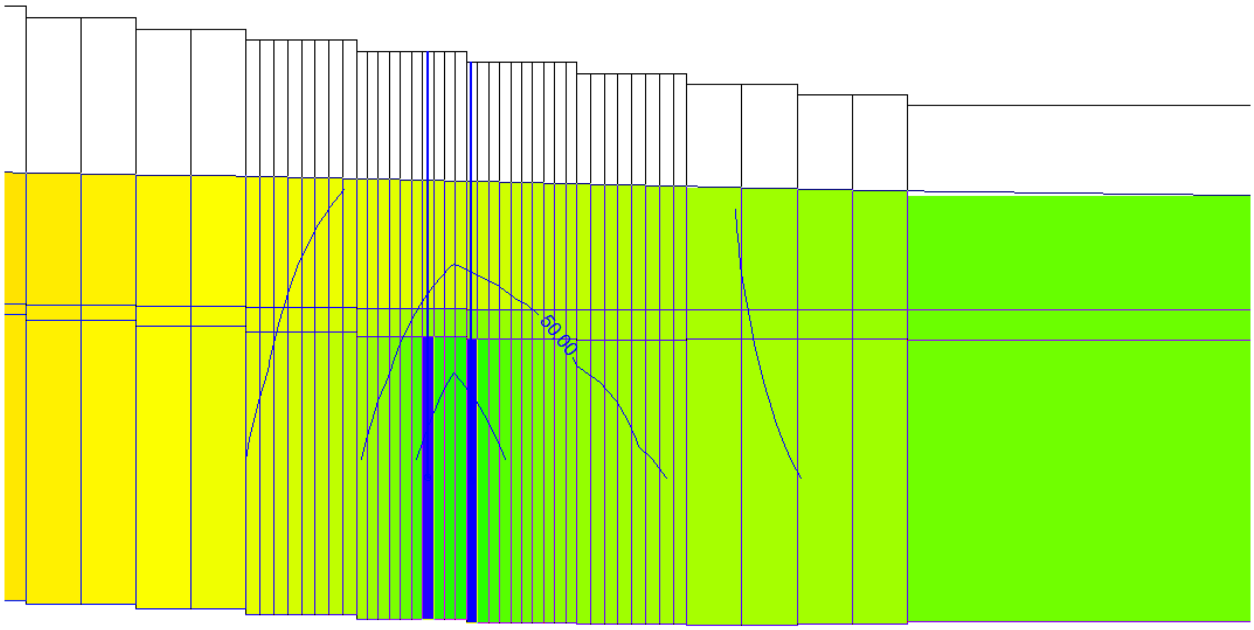
After the first basic cycle



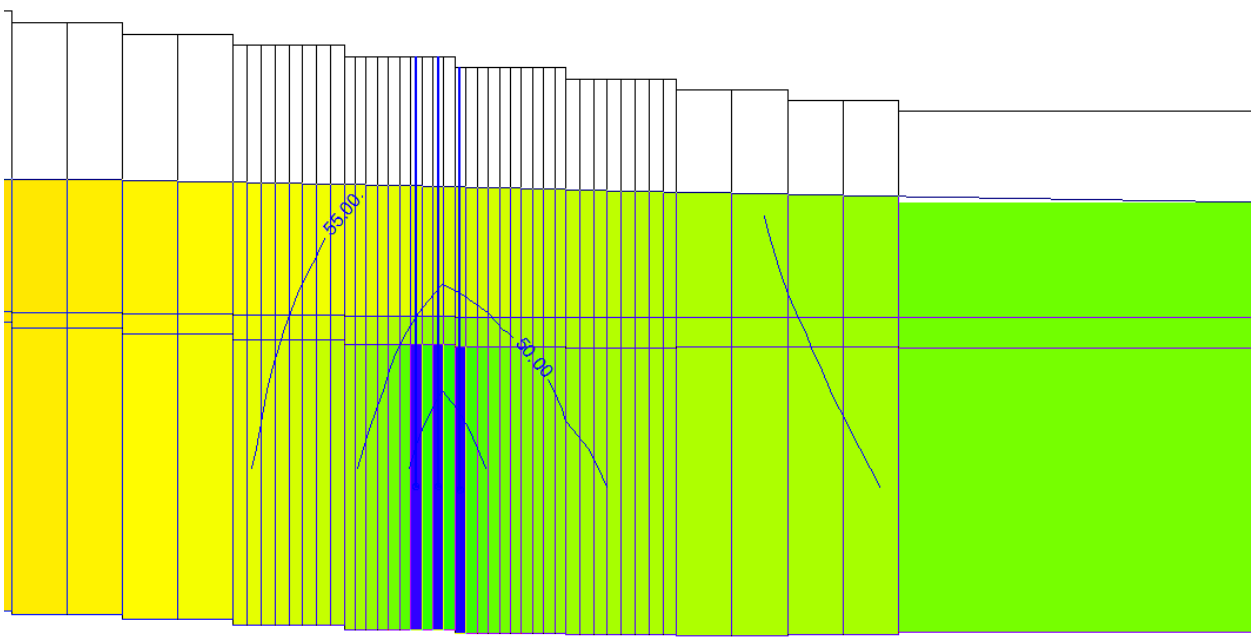
Cross-Section along Row 24



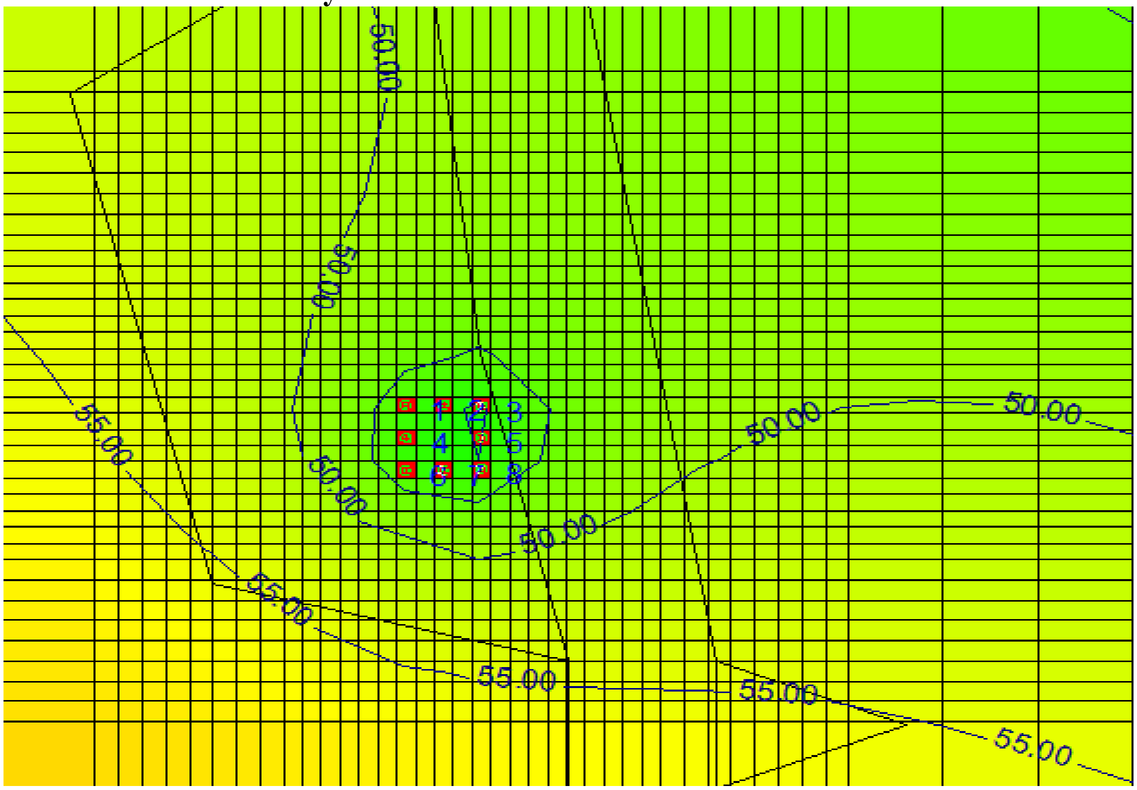
Cross-Section along Row 26



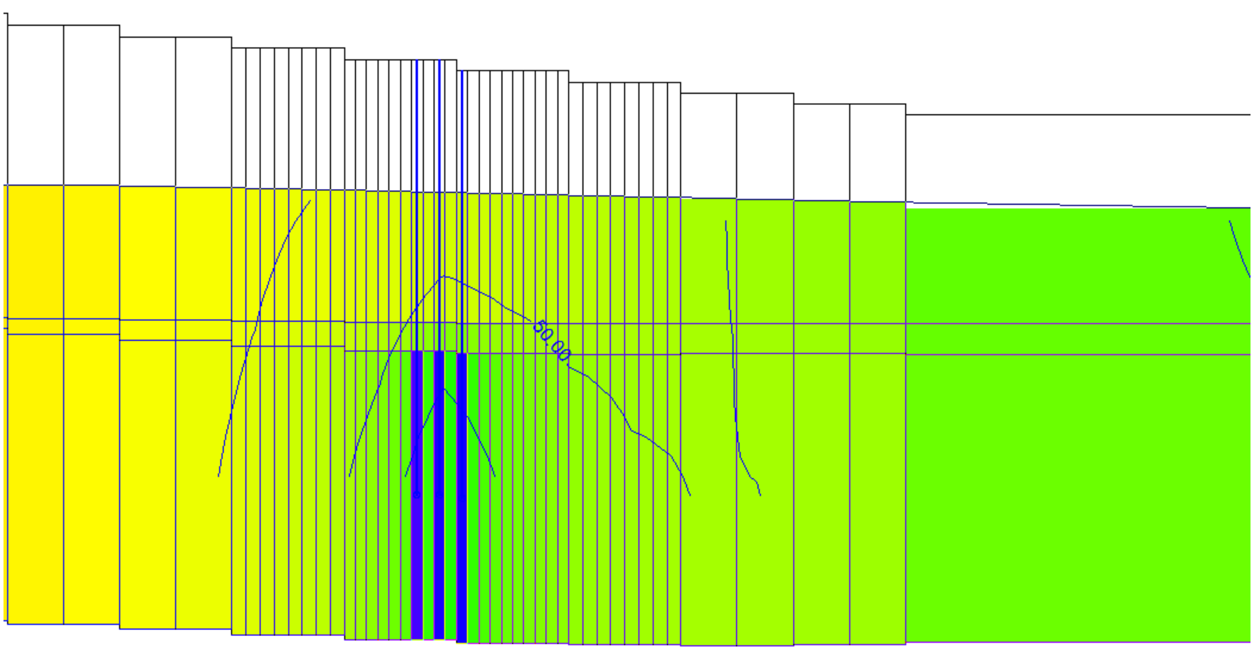
Cross-Section along Row 28



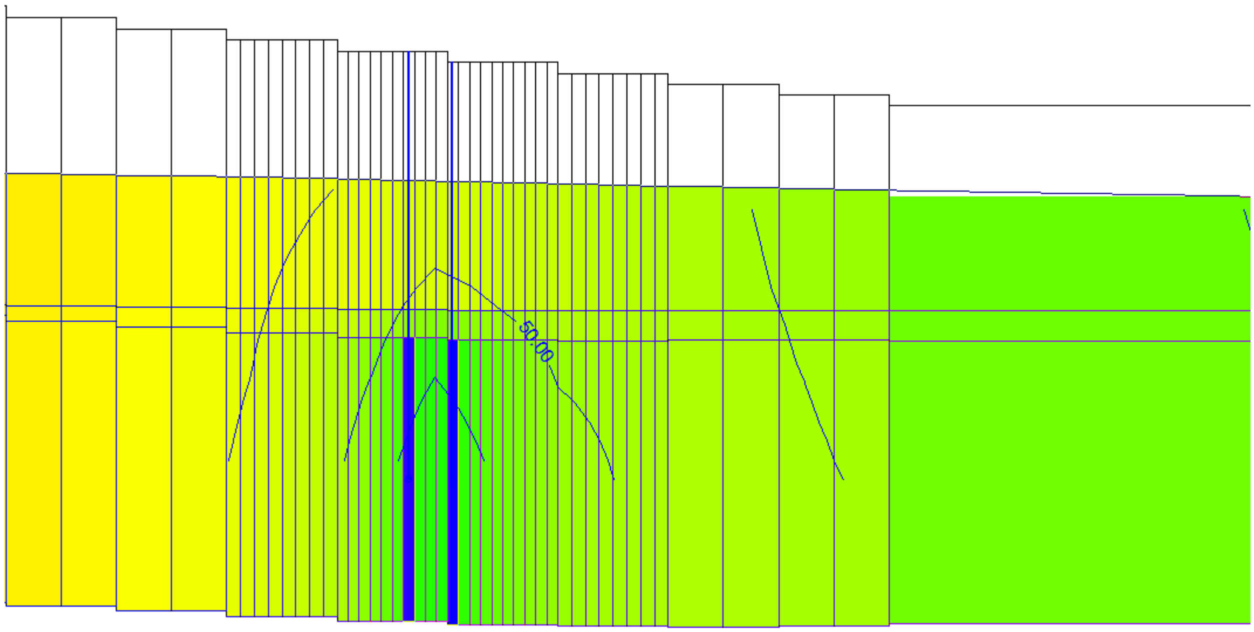
After the second basic cycles



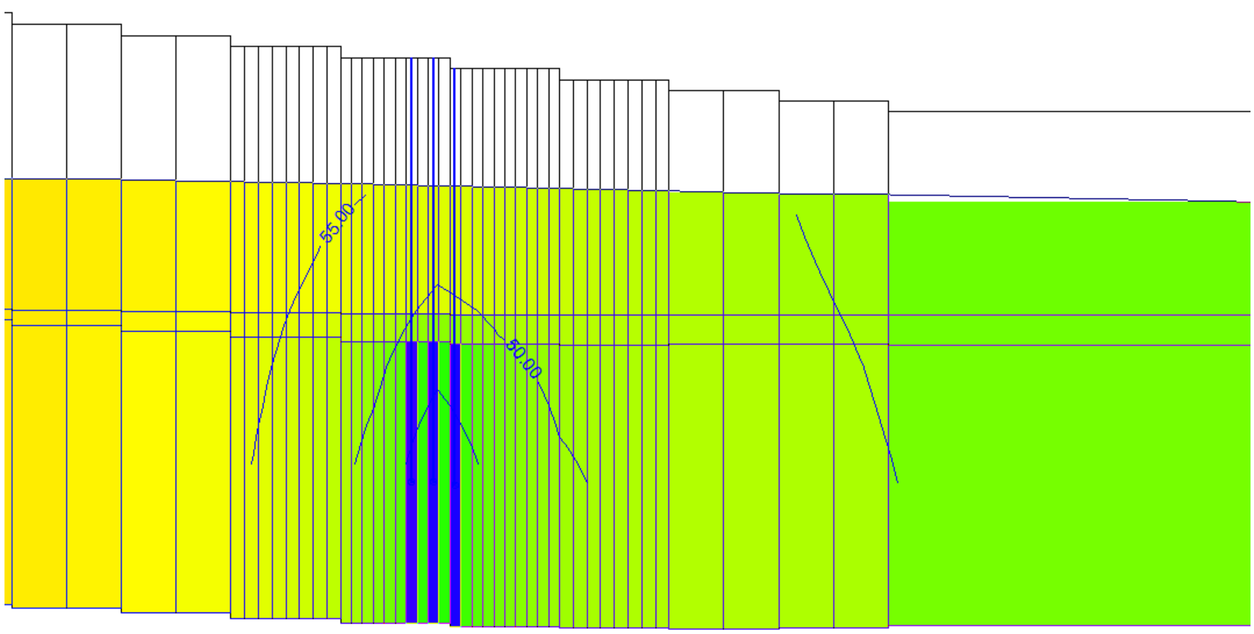
Cross-Section along Row 24



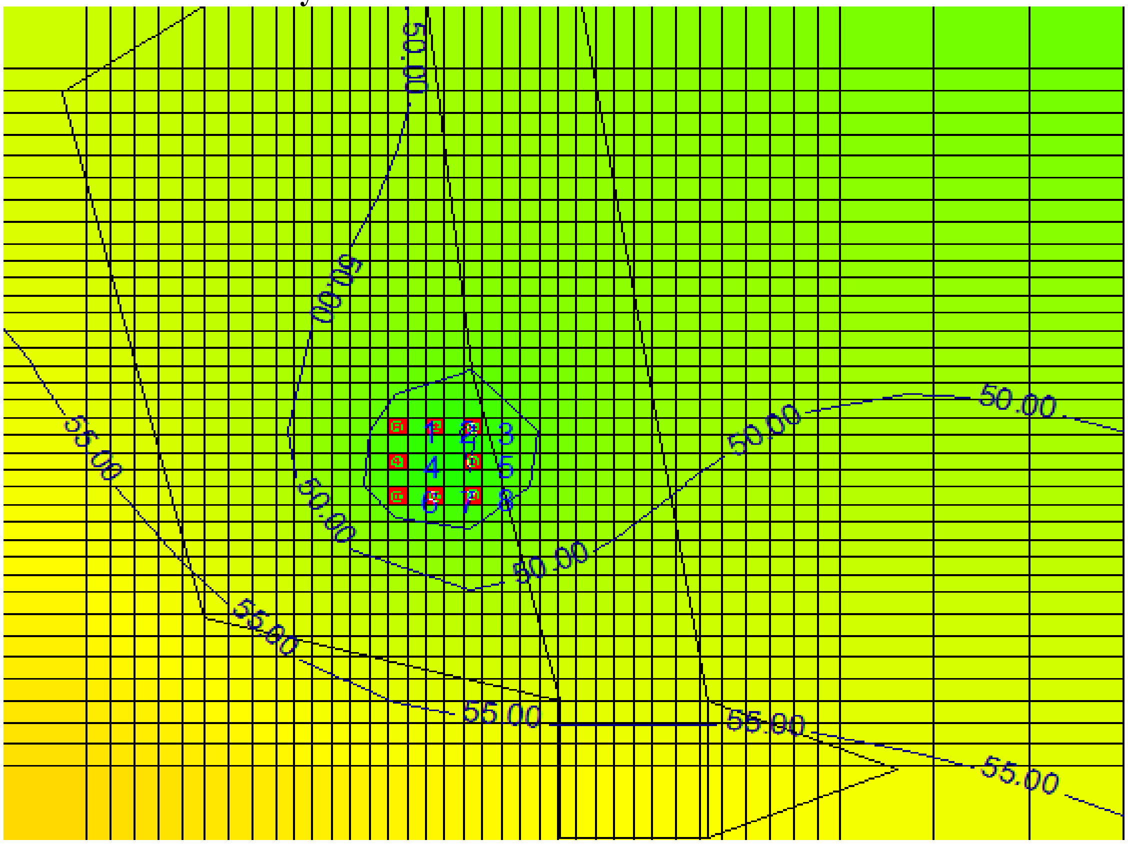
Cross-Section along Row 26



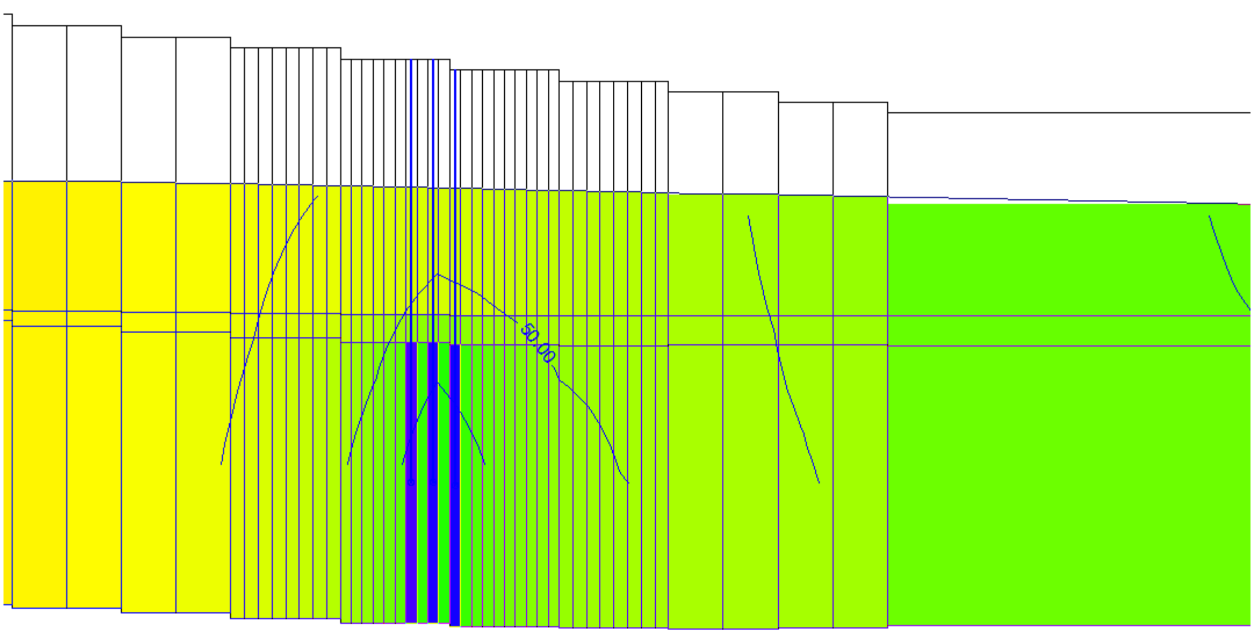
Cross-Section along Row 28



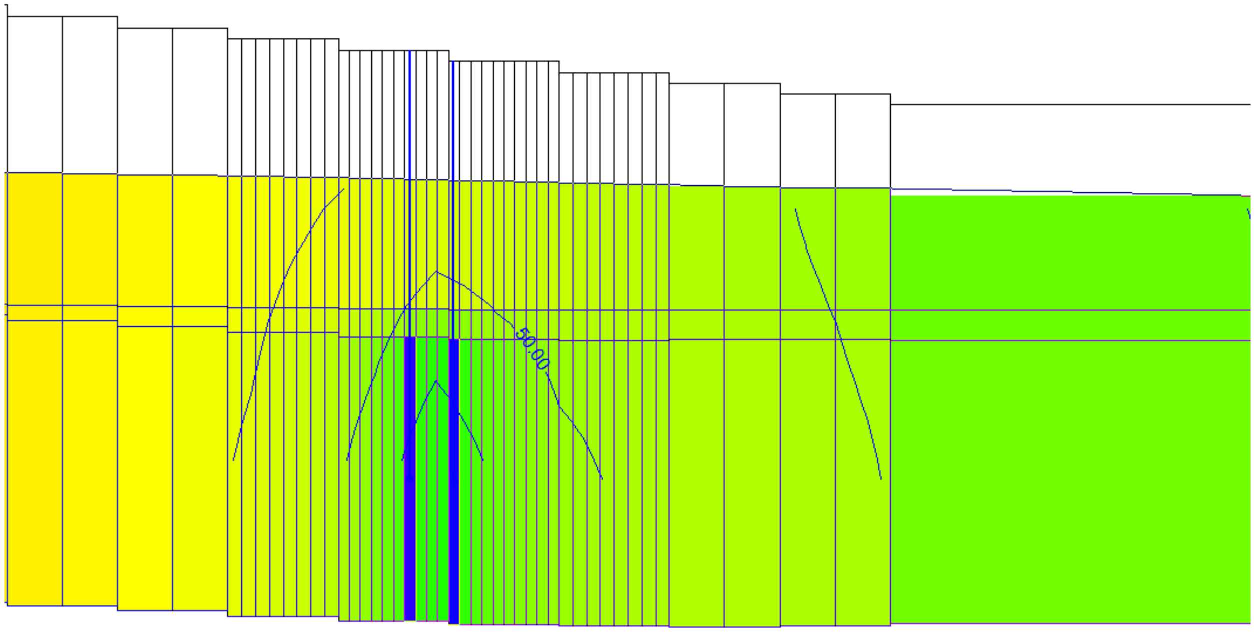
After the third basic cycles



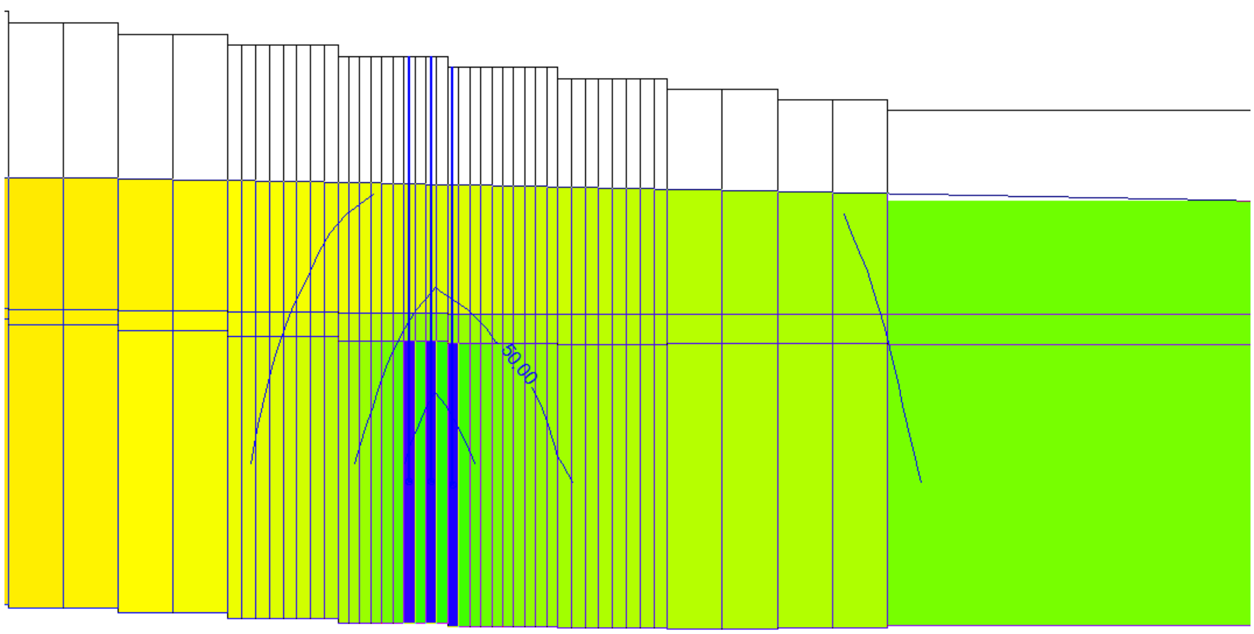
Cross-Section along Row 24

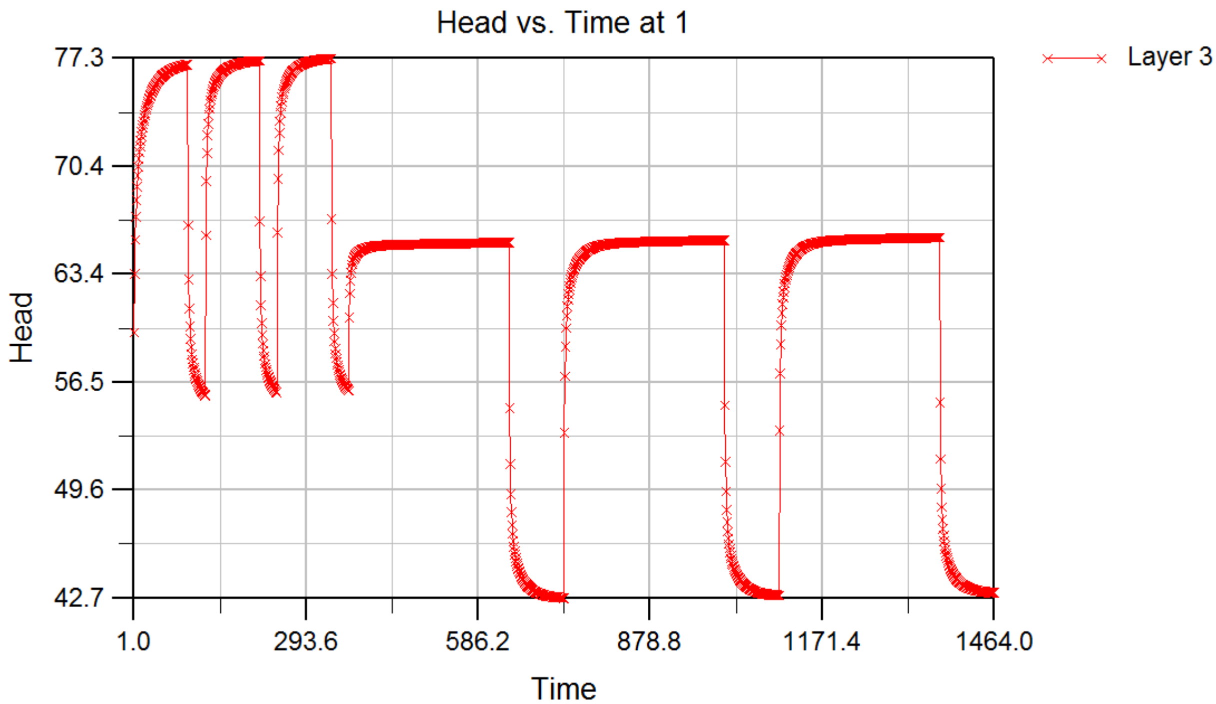


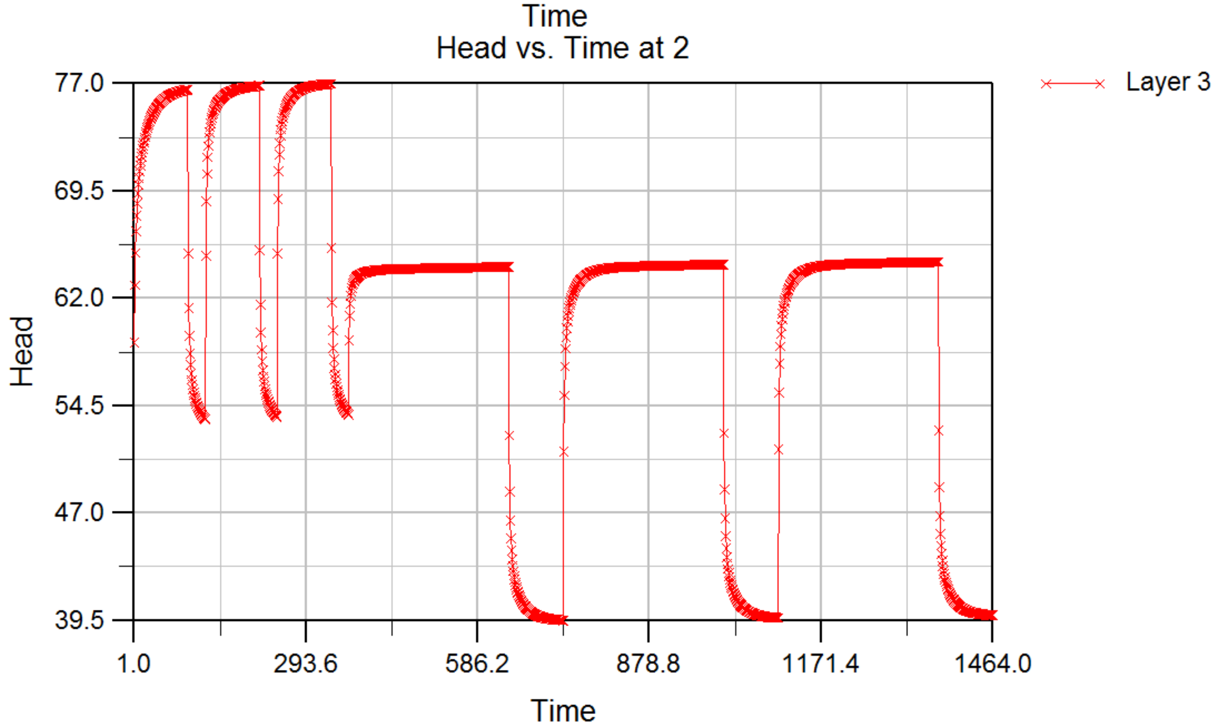
Cross-Section along Row 26

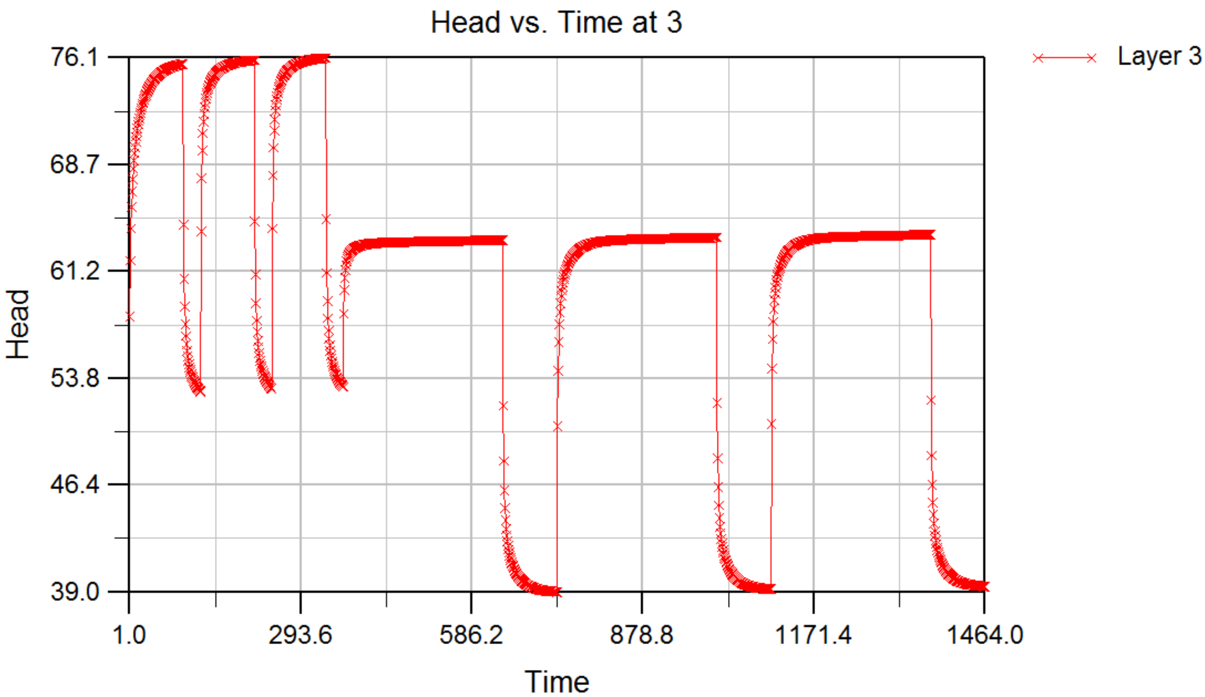


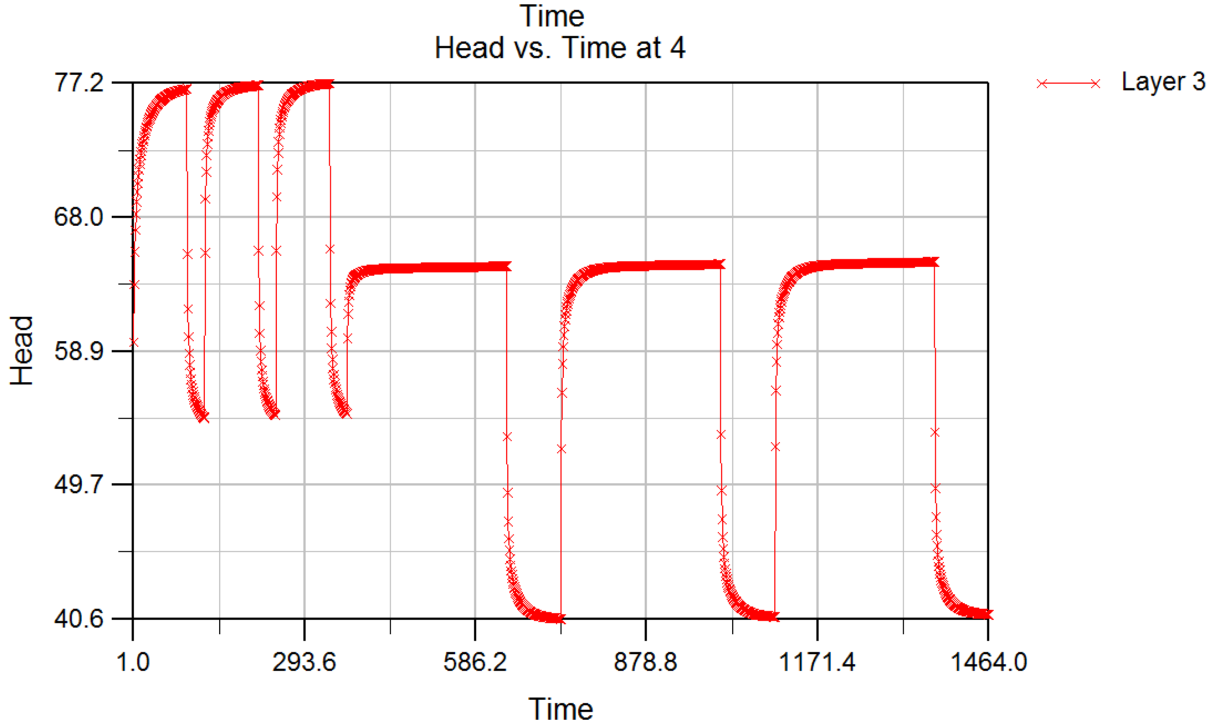
Cross-Section along Row 28

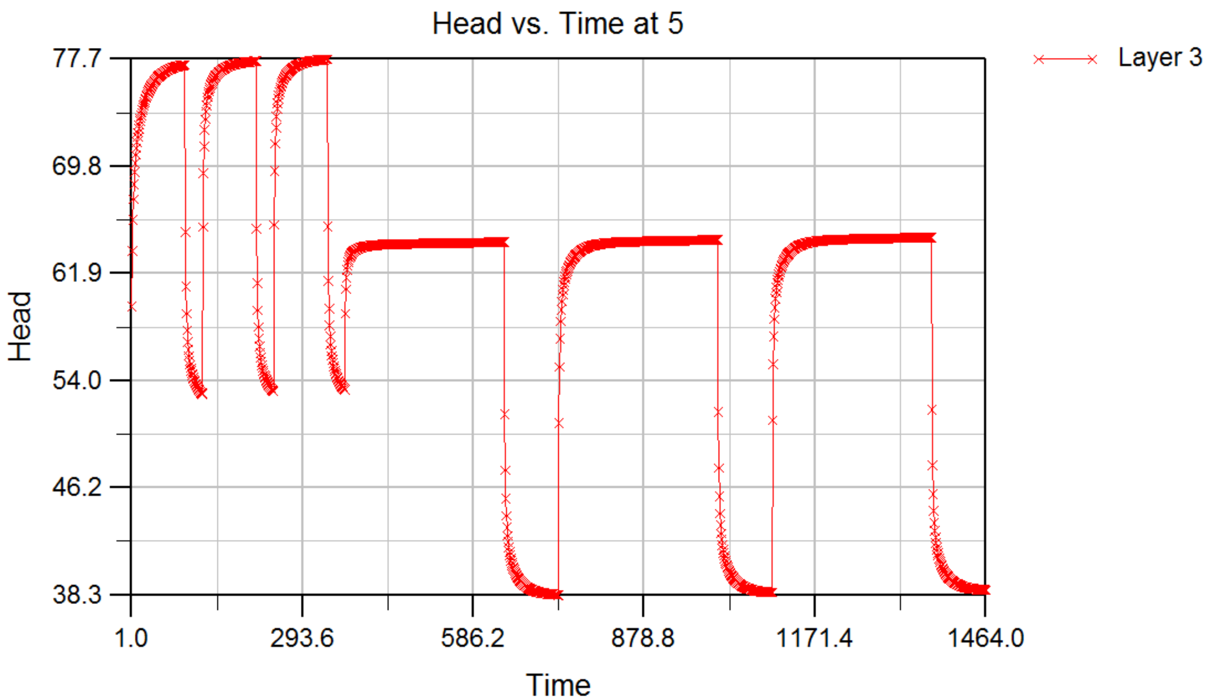



Head vs. Time at 1
Layer 3
77.3
70.4
63.4
56.5
49.6
42.7
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

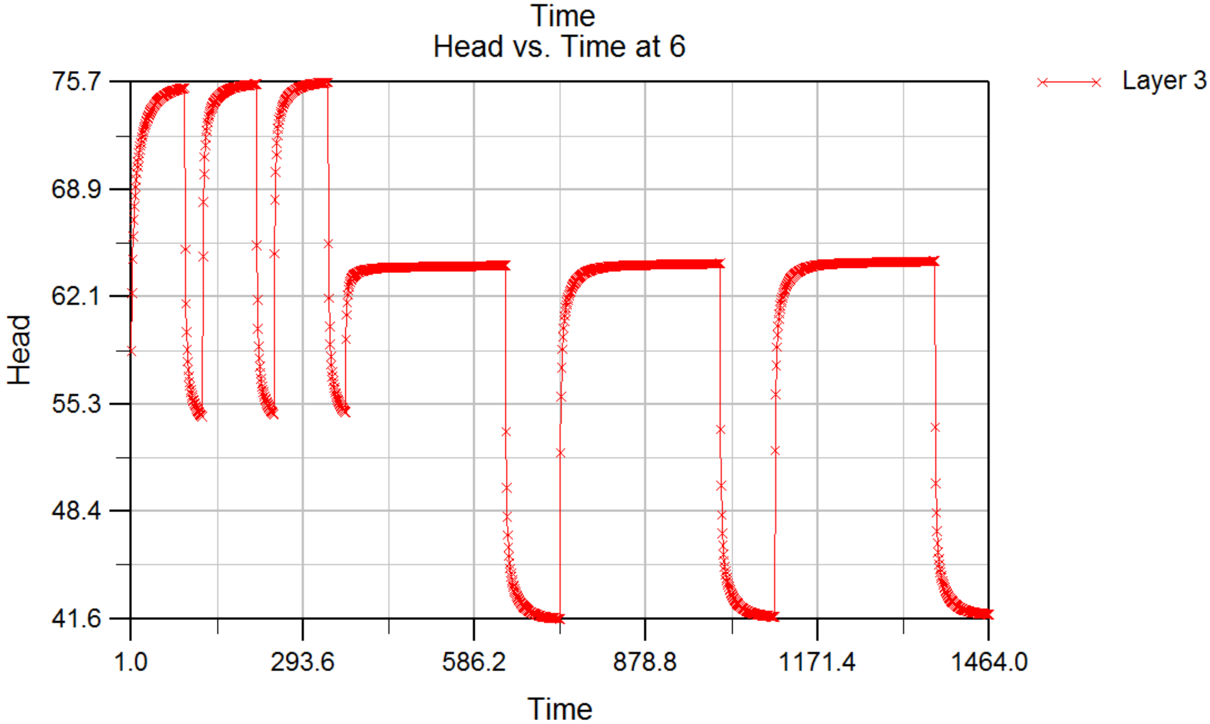

Head vs. Time at 2
Layer 3
77.0
69.5
62.0
54.5
47.0
39.5
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time


Head vs. Time at 3
Layer 3
76.1
68.7
61.2
53.8
46.4
39.0
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

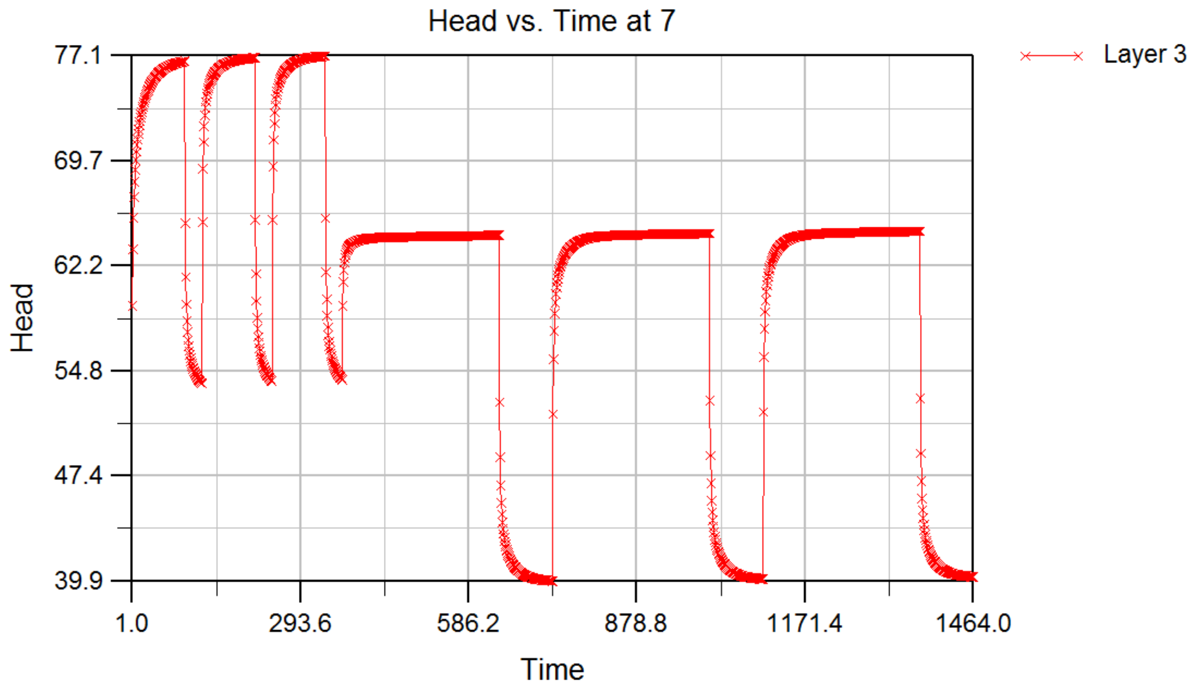

Head vs. Time at 4
Layer 3
77.2
68.0
58.9
49.7
40.6
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

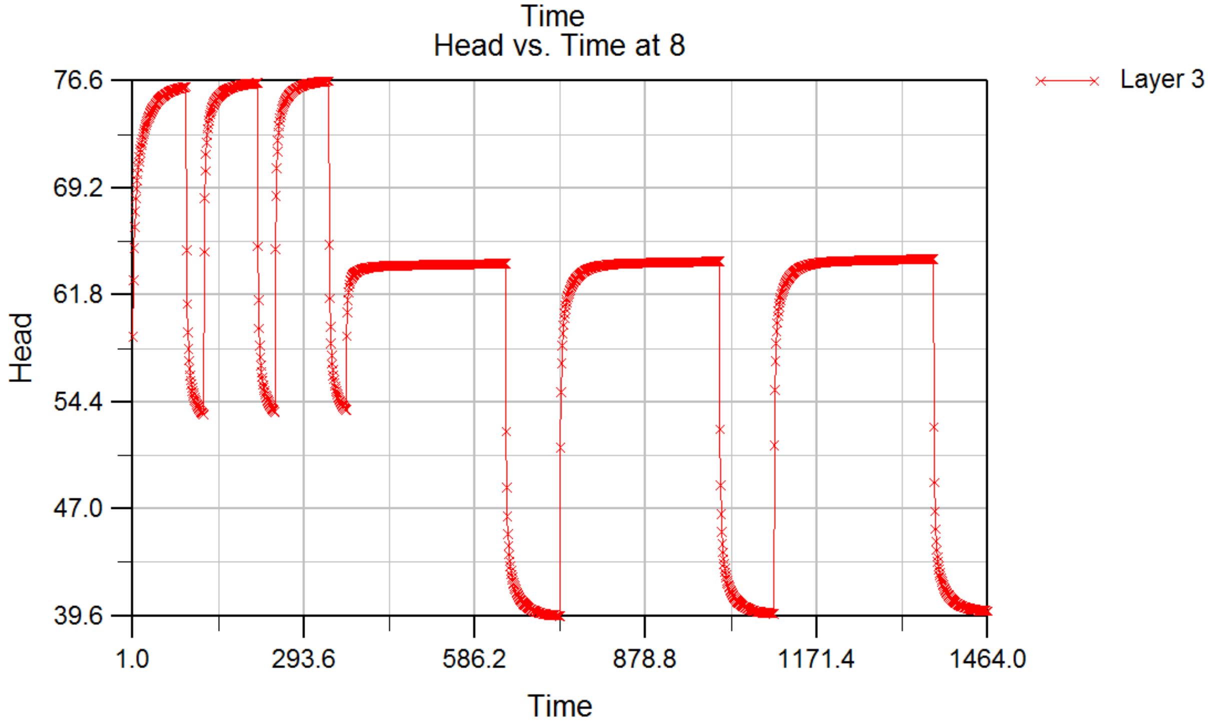


Head vs. Time at 5
Layer 3
Head
Time
77.7
69.8
61.9
54.0
46.2
38.3
1.0
293.6
586.2
878.8
1171.4
1464.0



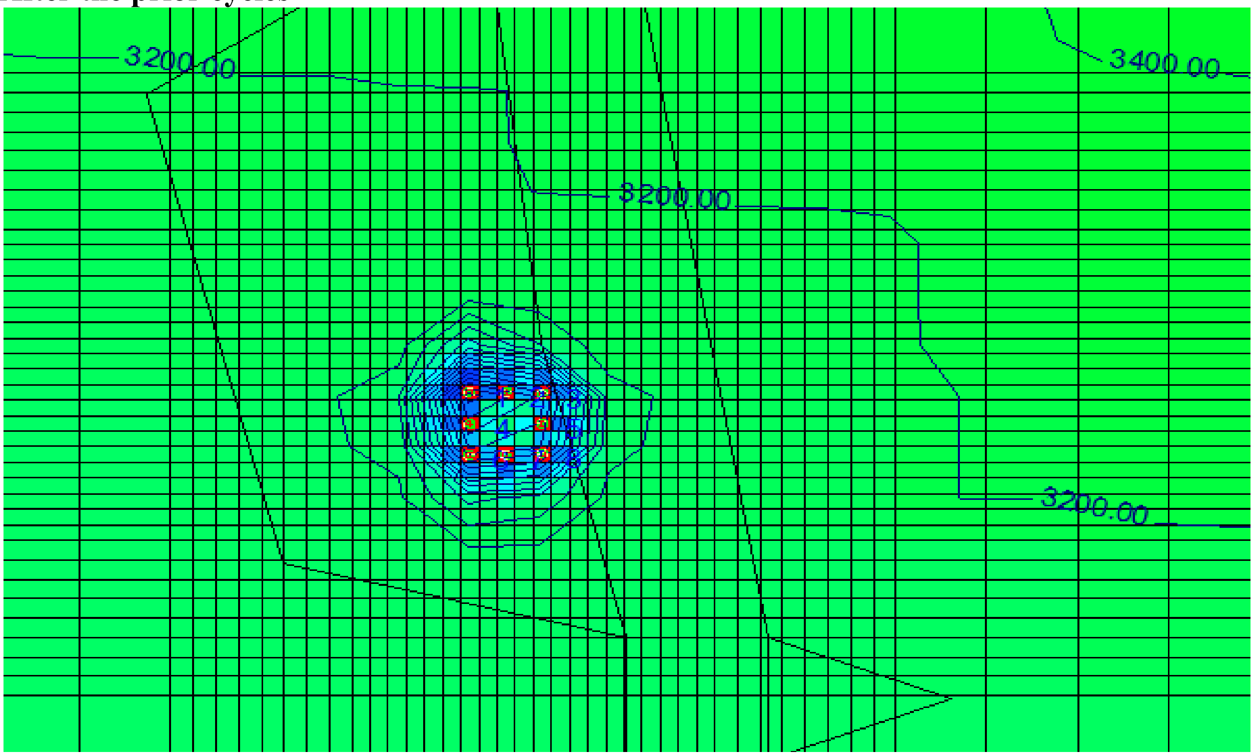
Head vs. Time at 6
Layer 3
Head
Time
75.7
68.9
62.1
55.3
48.4
41.6
1.0
293.6
586.2
878.8
1171.4
1464.0


Head vs. Time at 7
Layer 3
77.1
69.7
62.2
54.8
47.4
39.9
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

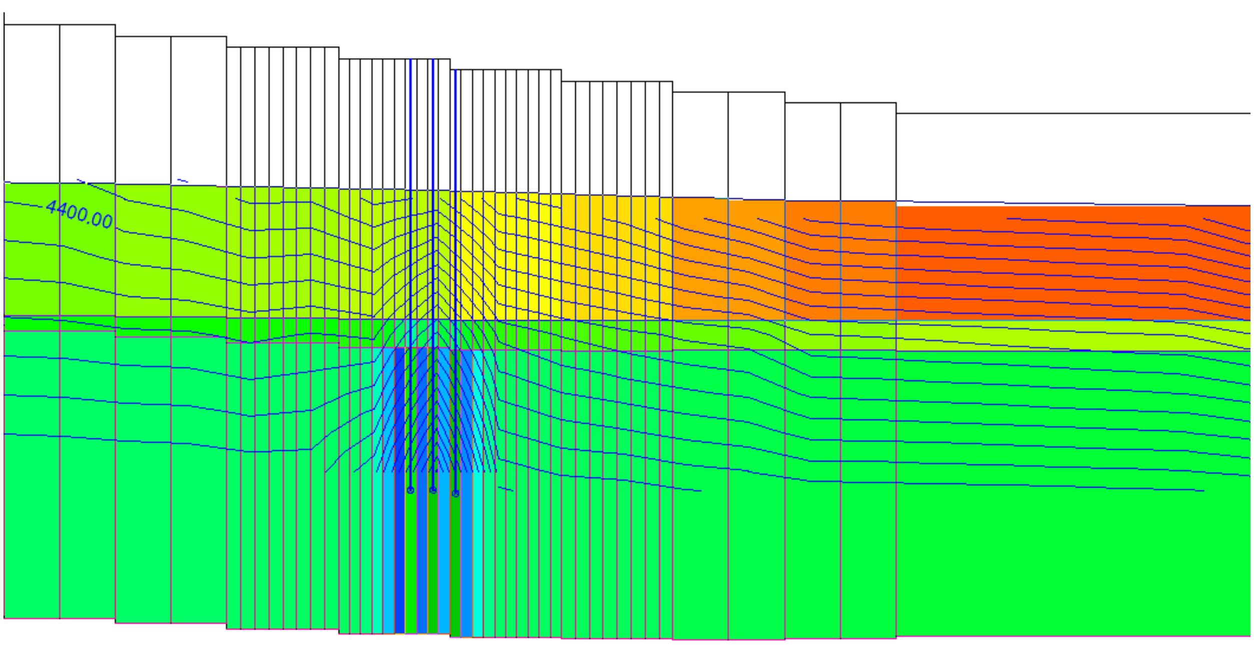

Head vs. Time at 8
Layer 3
76.6
69.2
61.8
54.4
47.0
39.6
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

RUN 3 MT3D

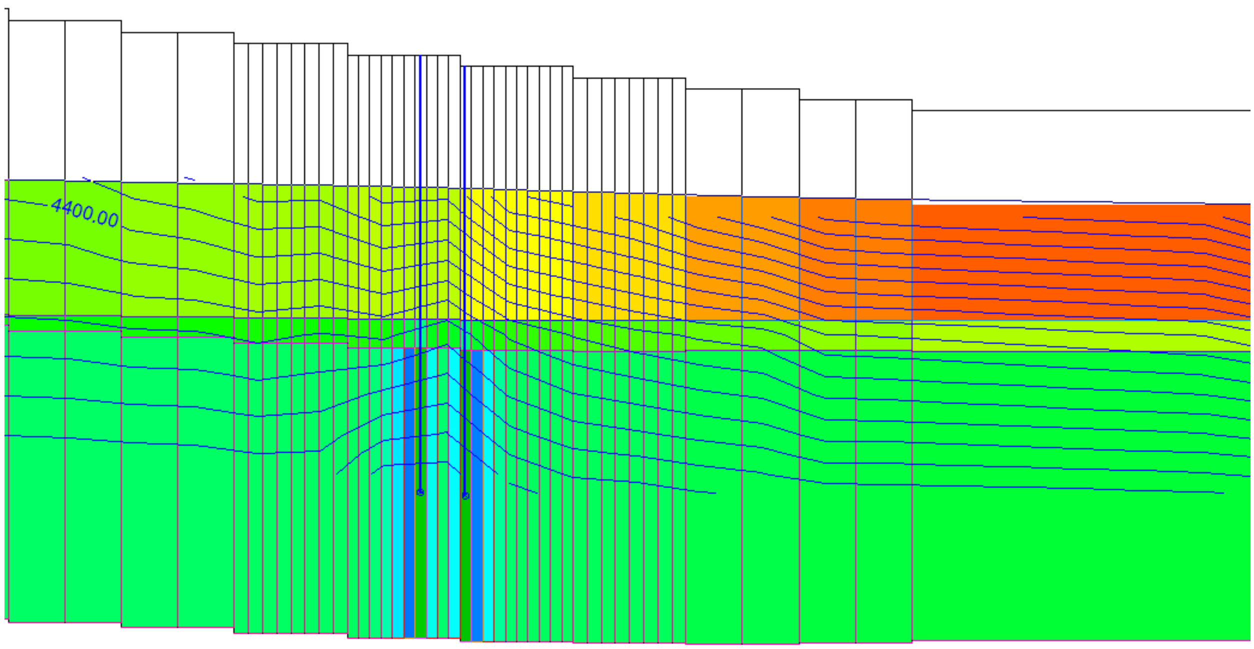
After the prior cycles



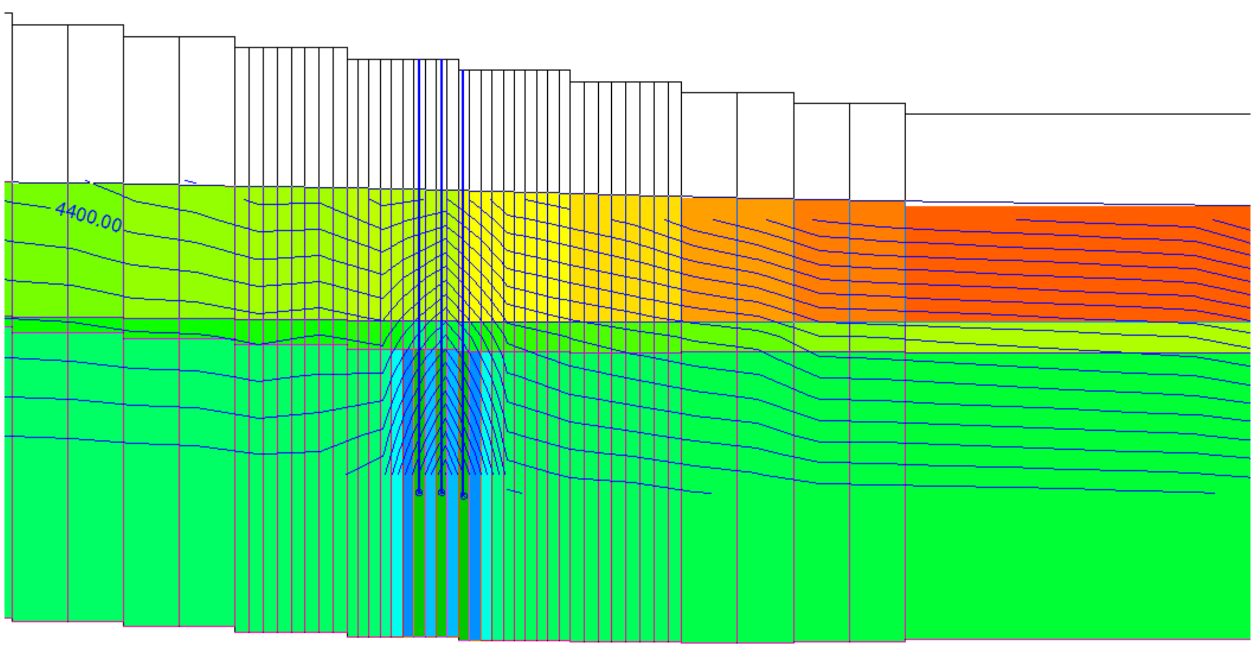
Cross-Section along Row 24



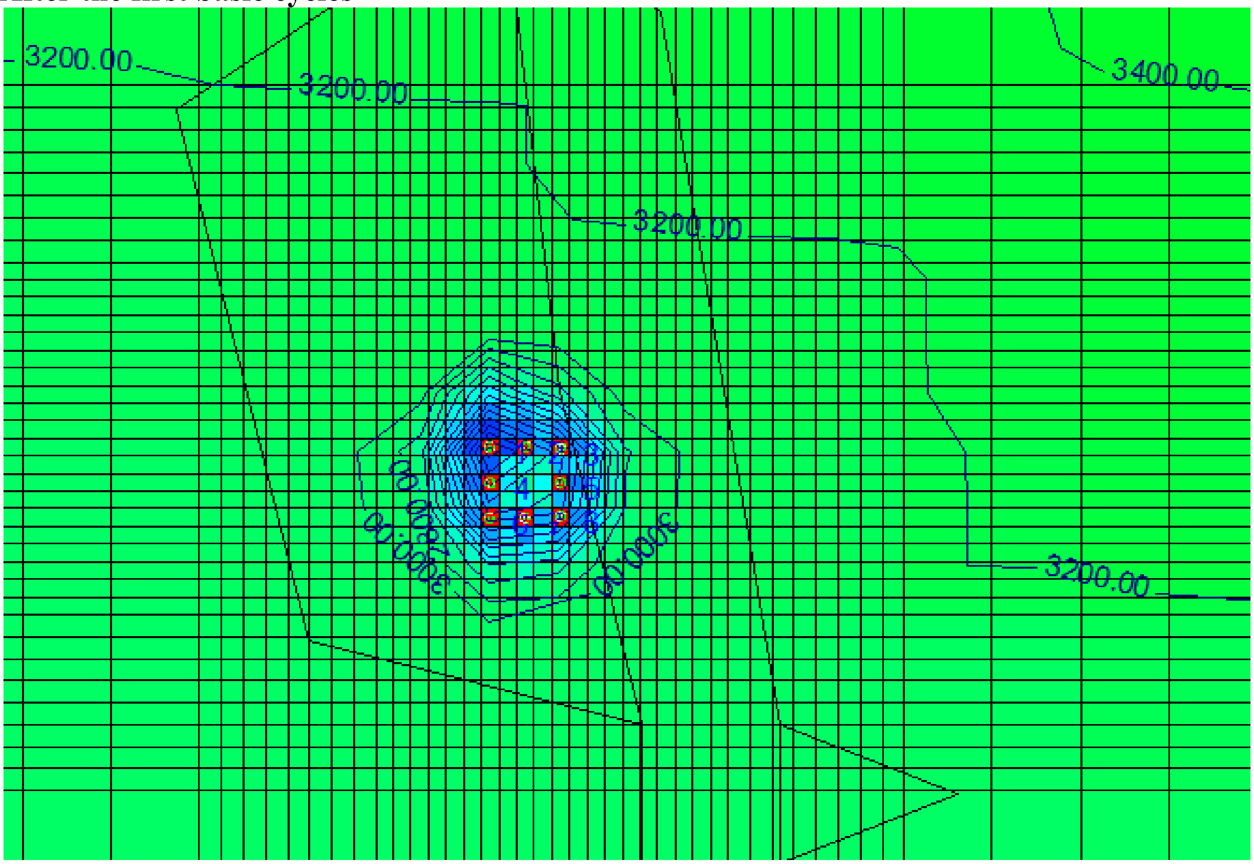
Cross-Section along Row 26



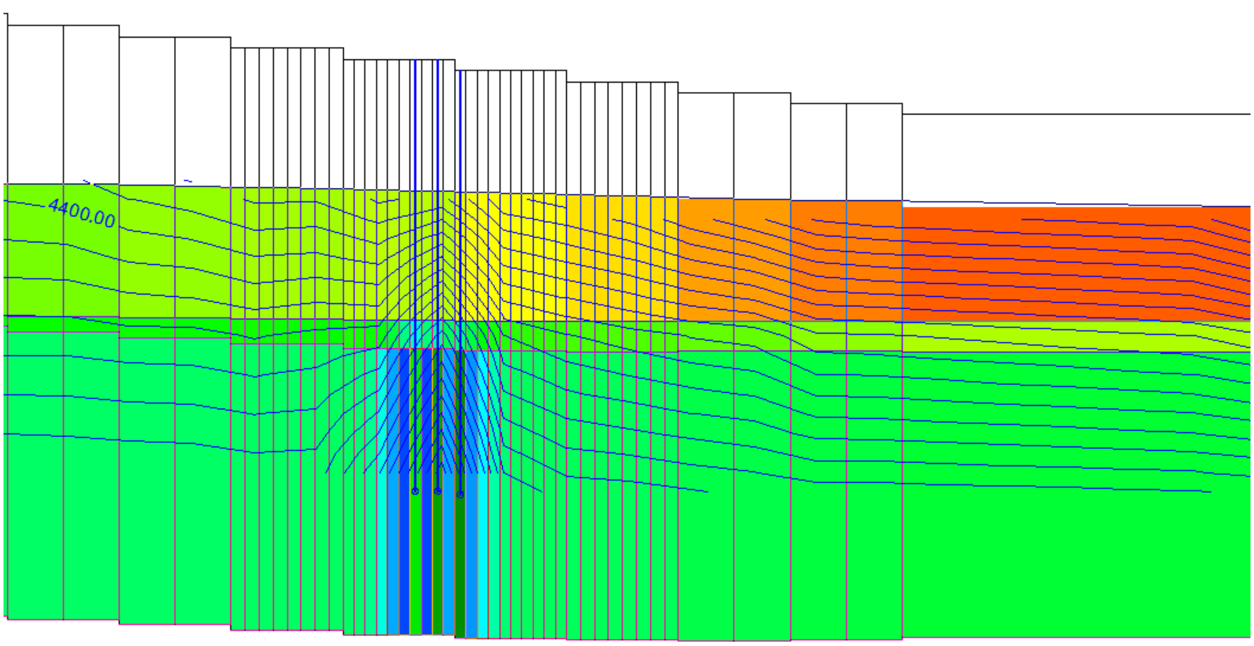
Cross-Section along Row 28



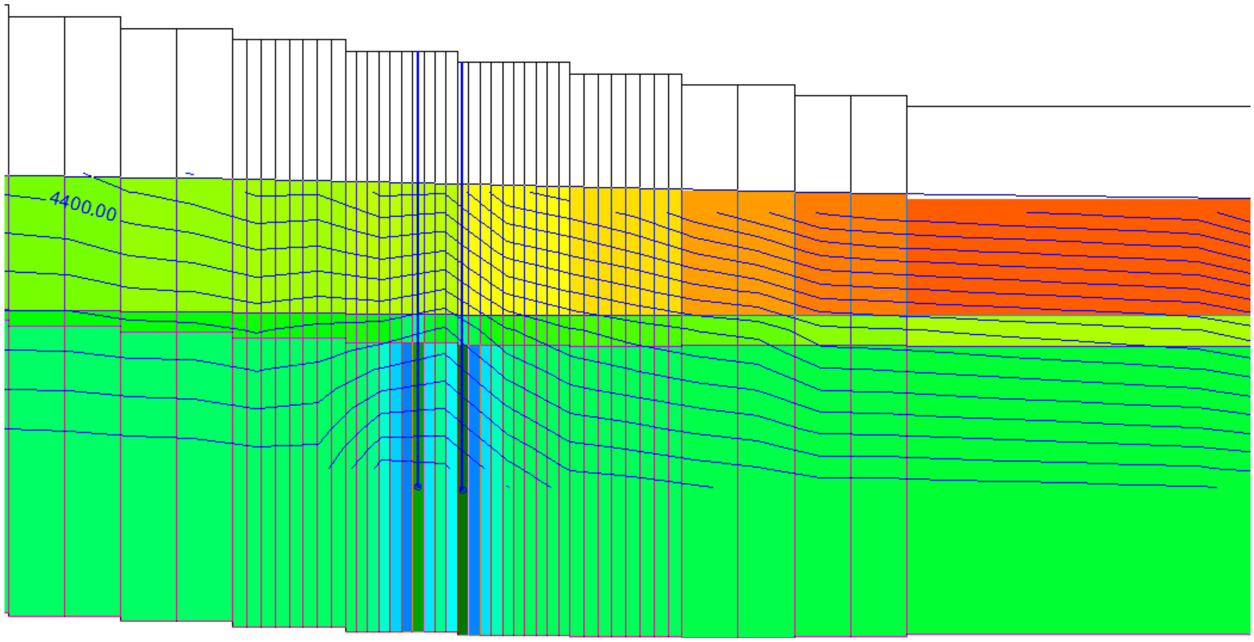
After the first basic cycles



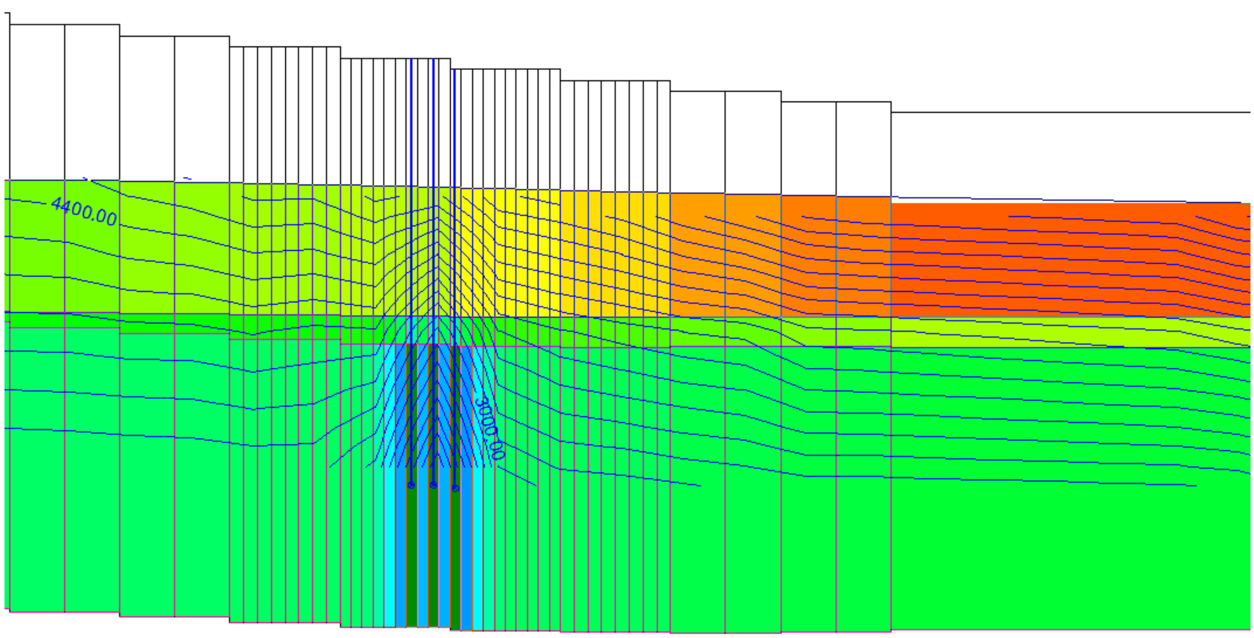
Cross-Section along Row 24



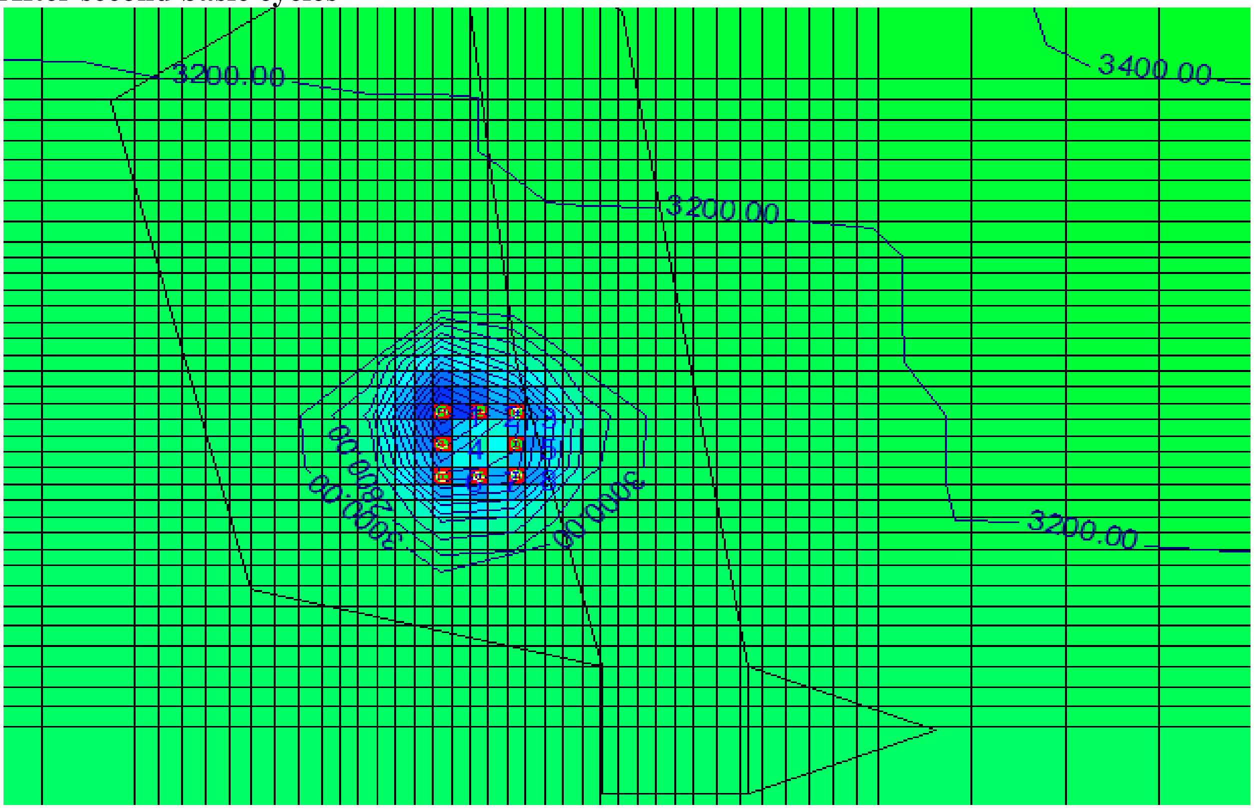
Cross-Section along Row 26



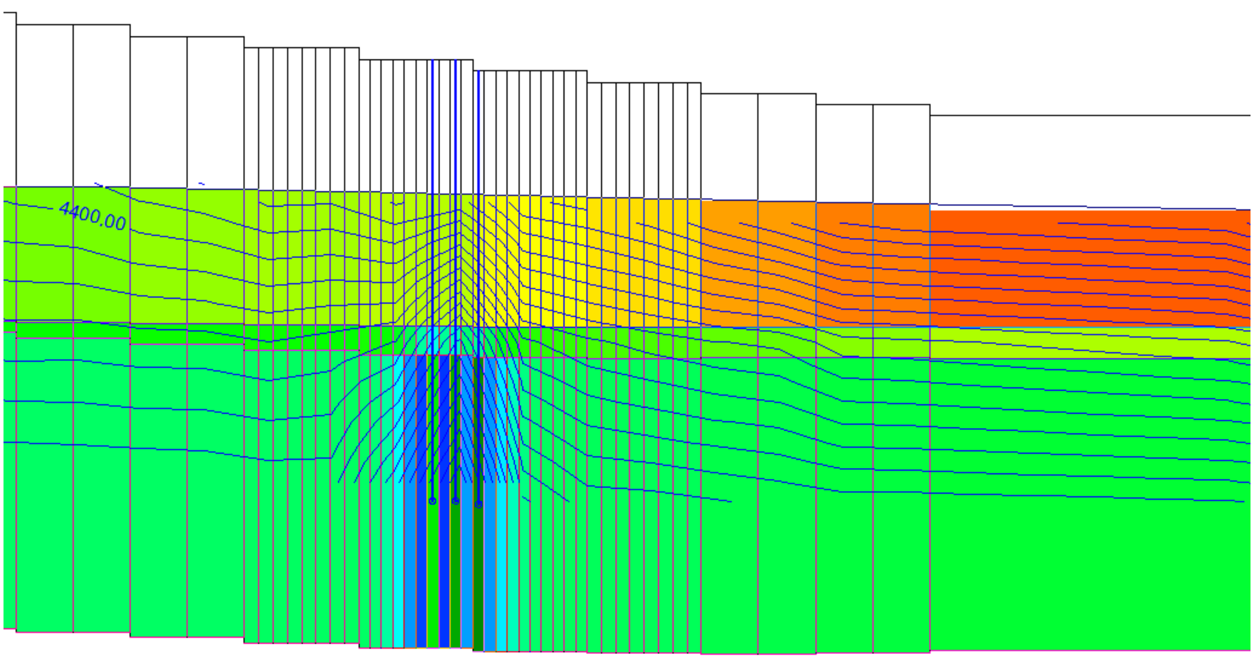
Cross-Section along Row 28



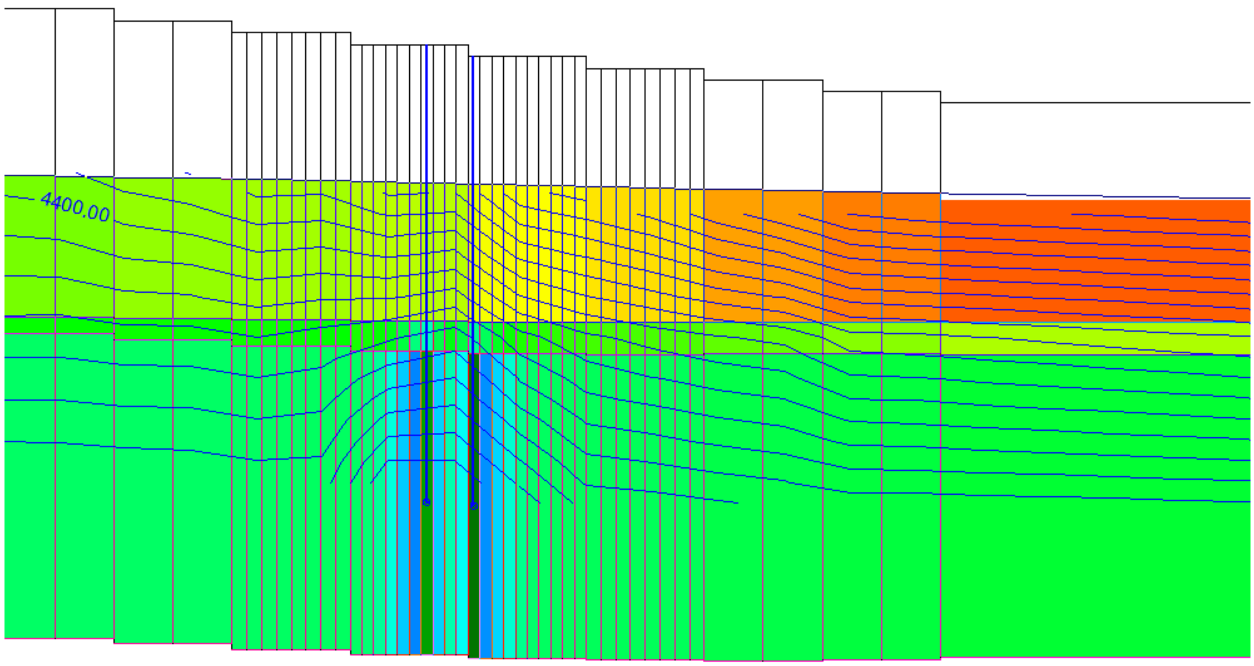
After second basic cycles



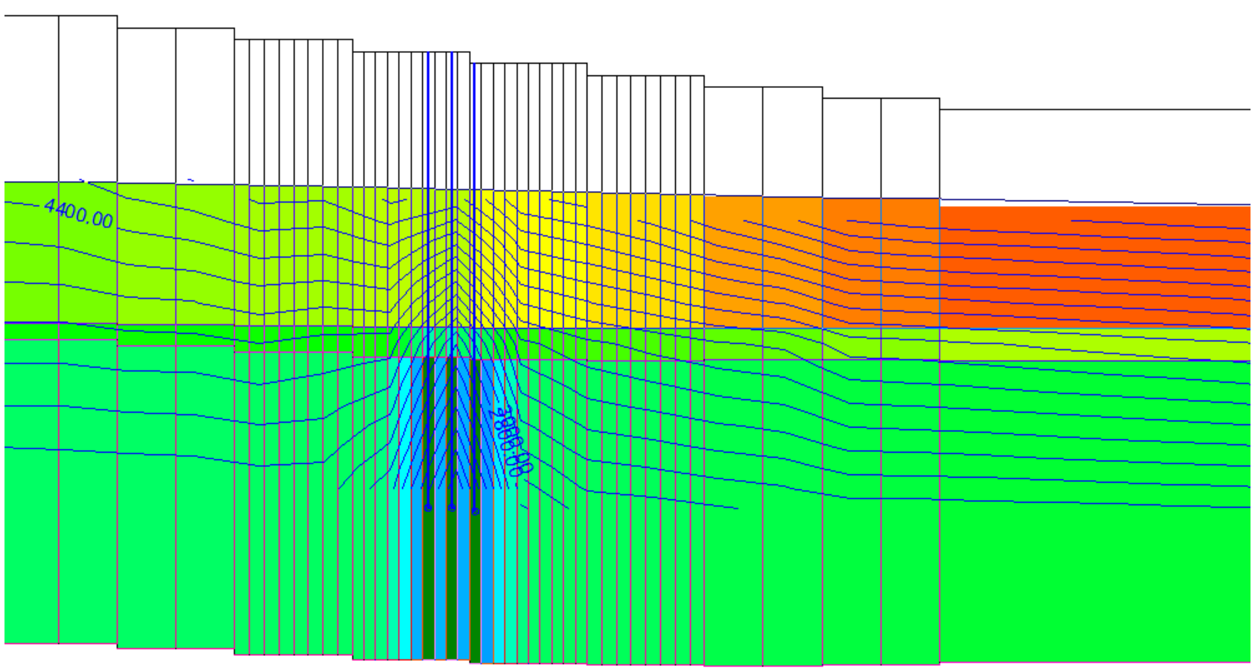
Cross-Section along Row 24



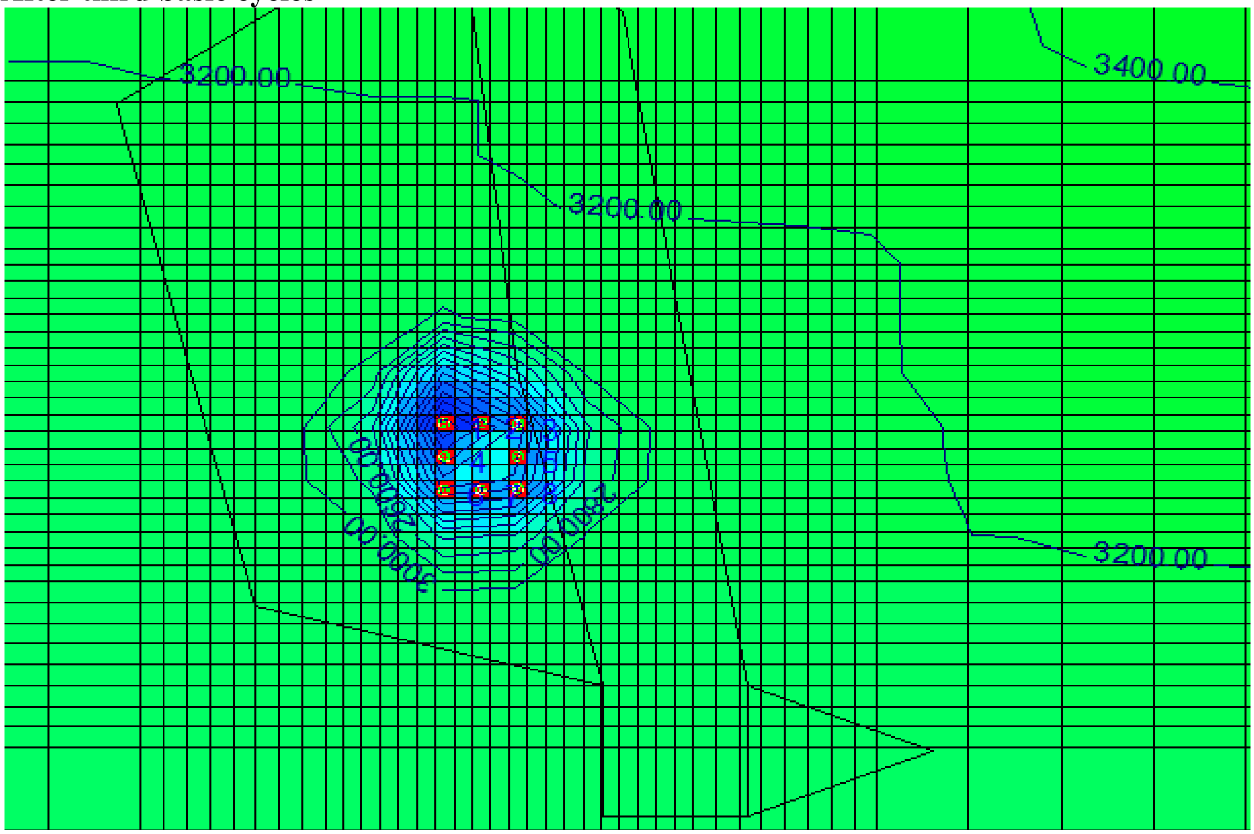
Cross-Section along Row 26



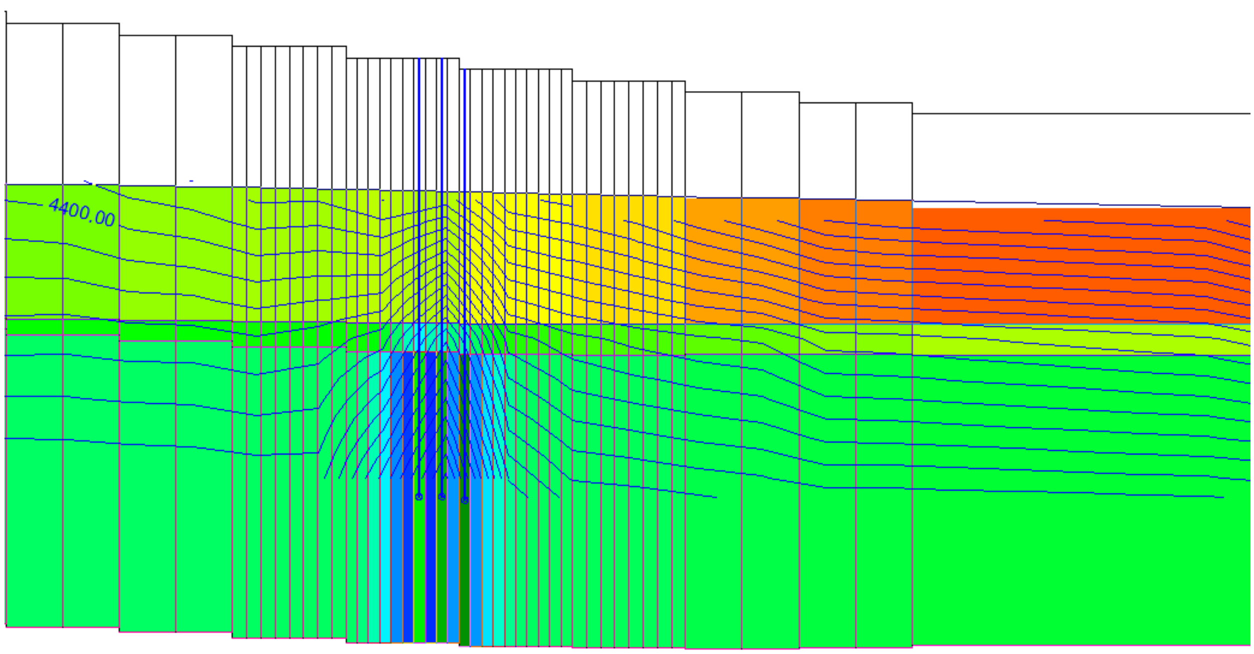
Cross-Section along Row 28



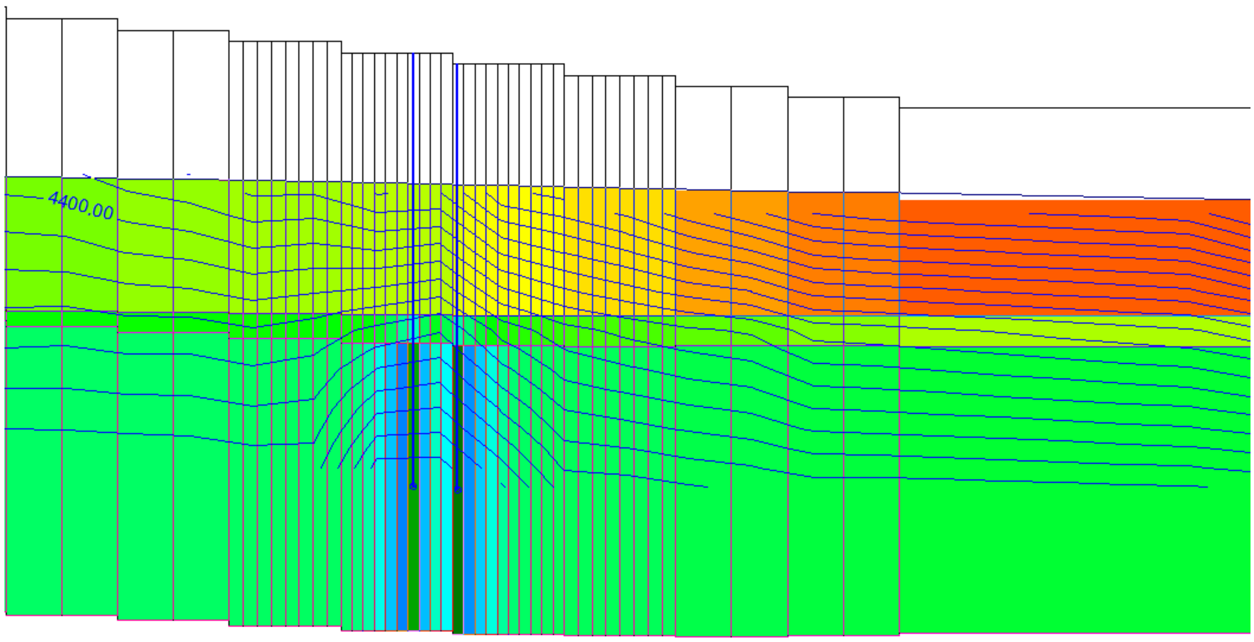
After third basic cycles



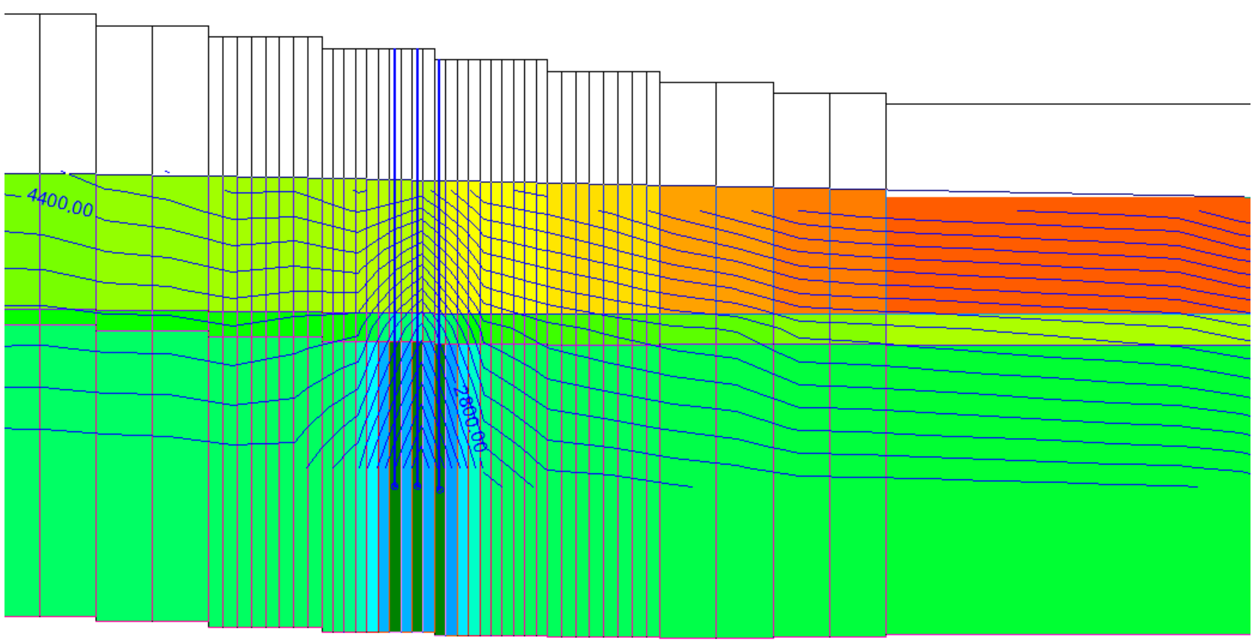
Cross-Section along Row 24

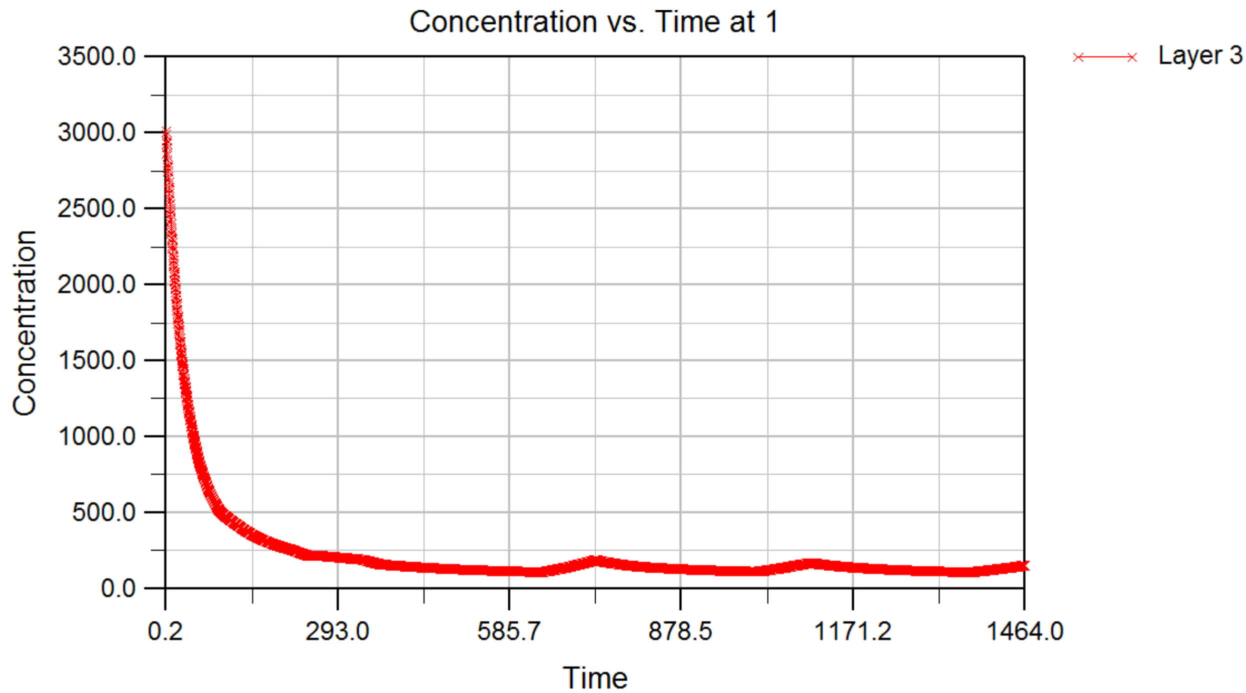


Cross-Section along Row 26

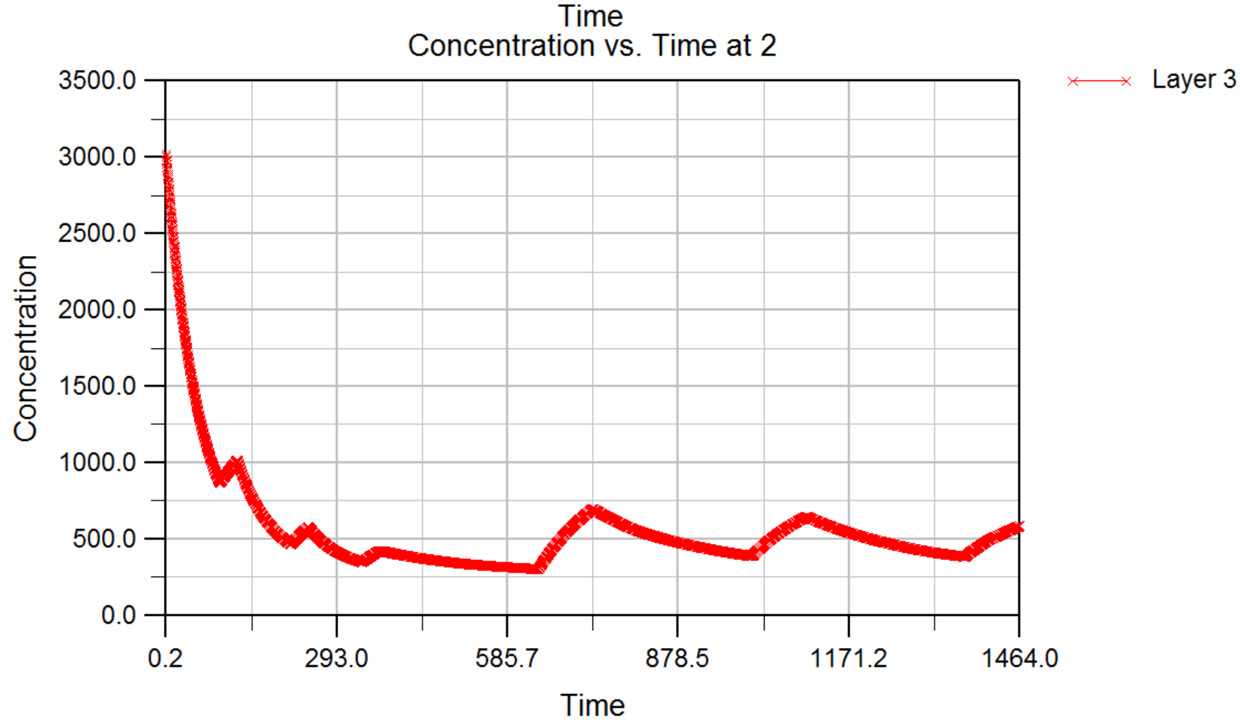


Cross-Section along Row 28

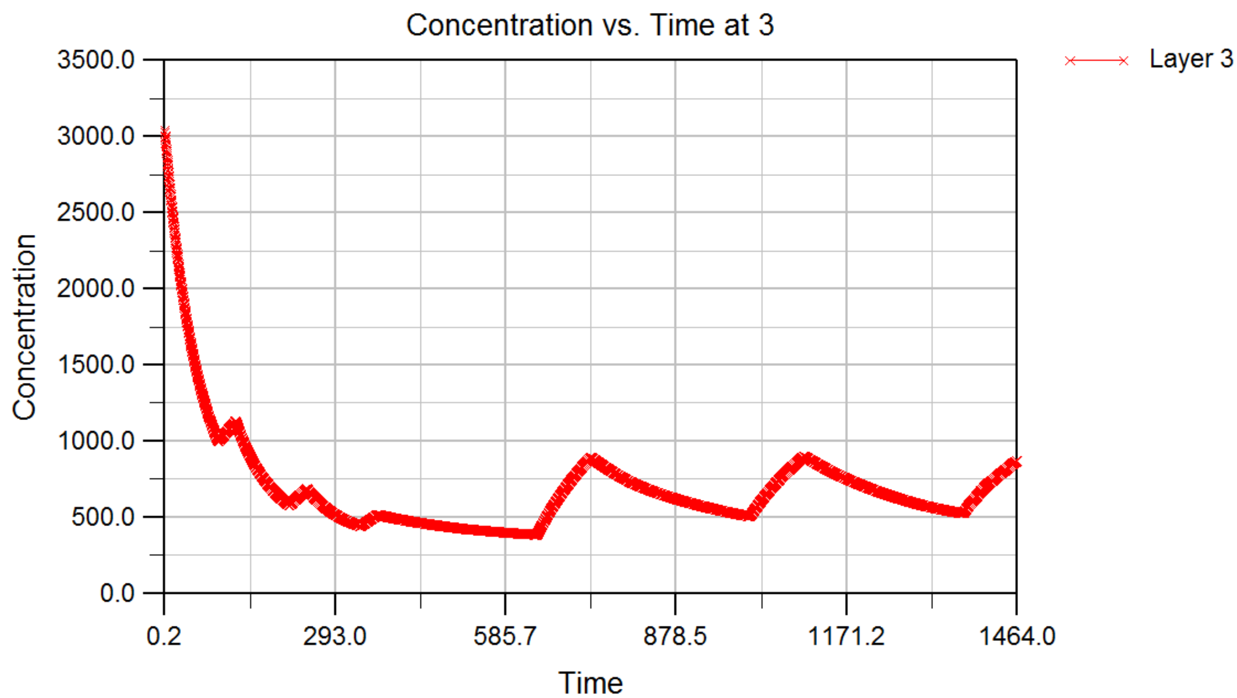


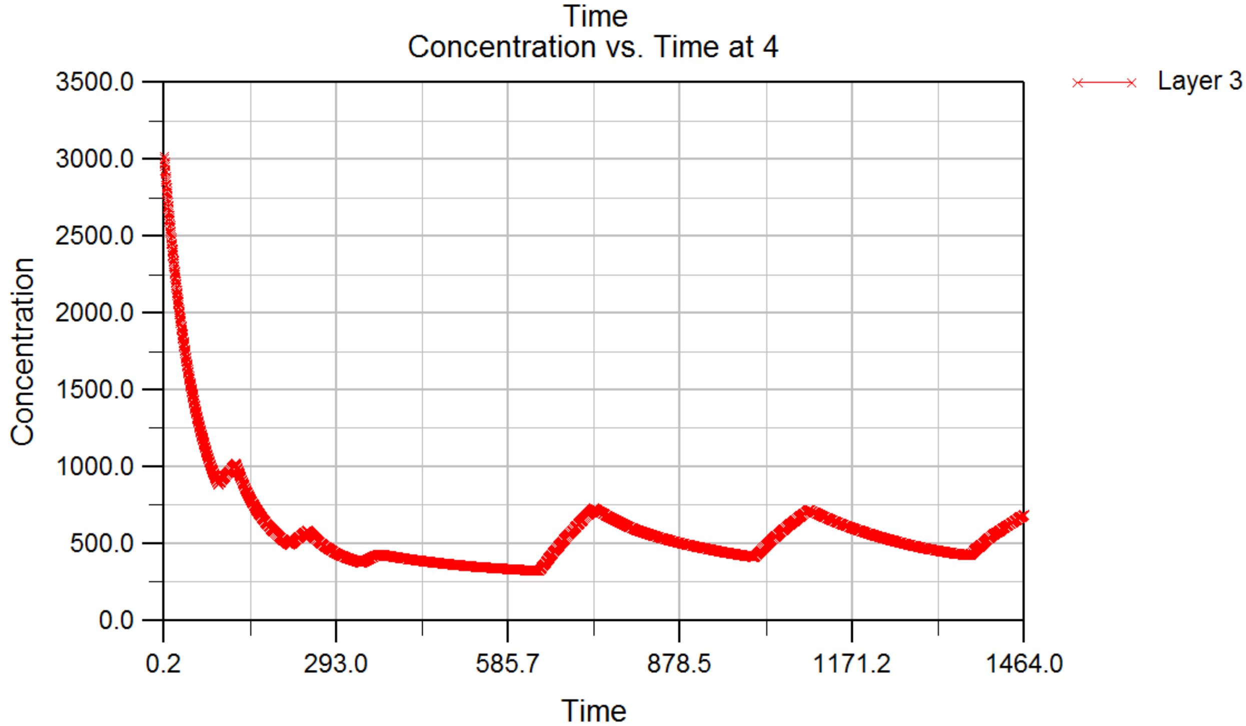


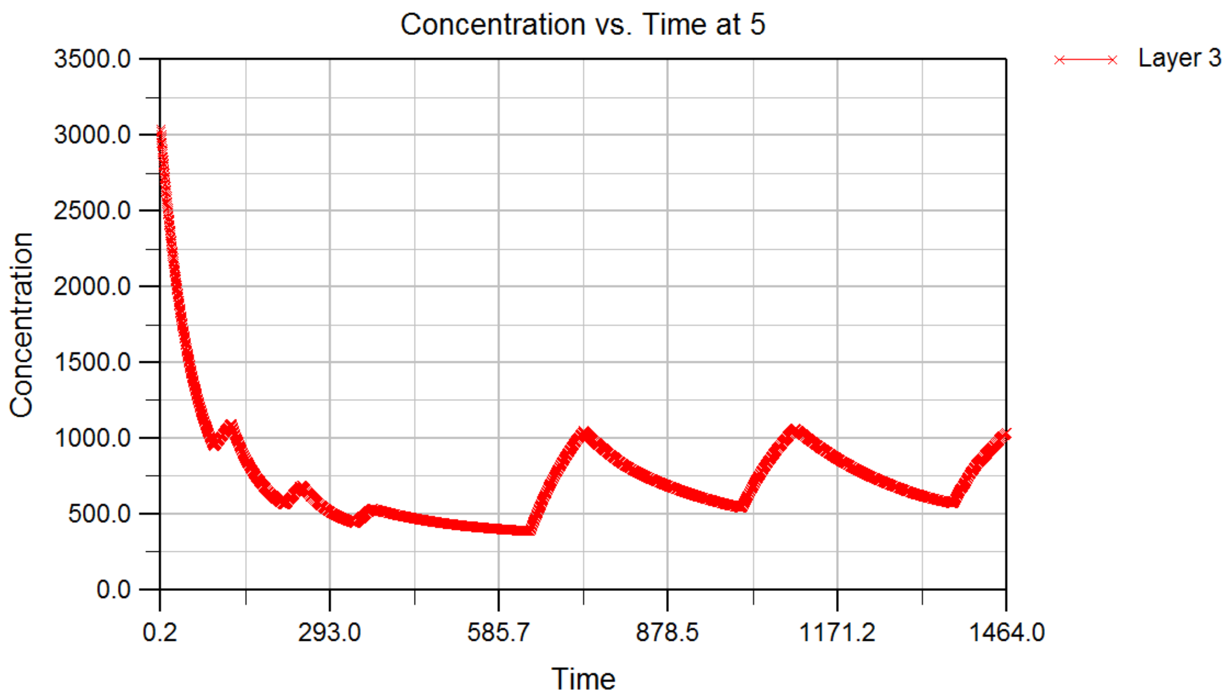
Concentration vs. Time at 1
Layer 3
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
Concentration
0.2
293.0
585.7
878.5
1171.2
1464.0
Time

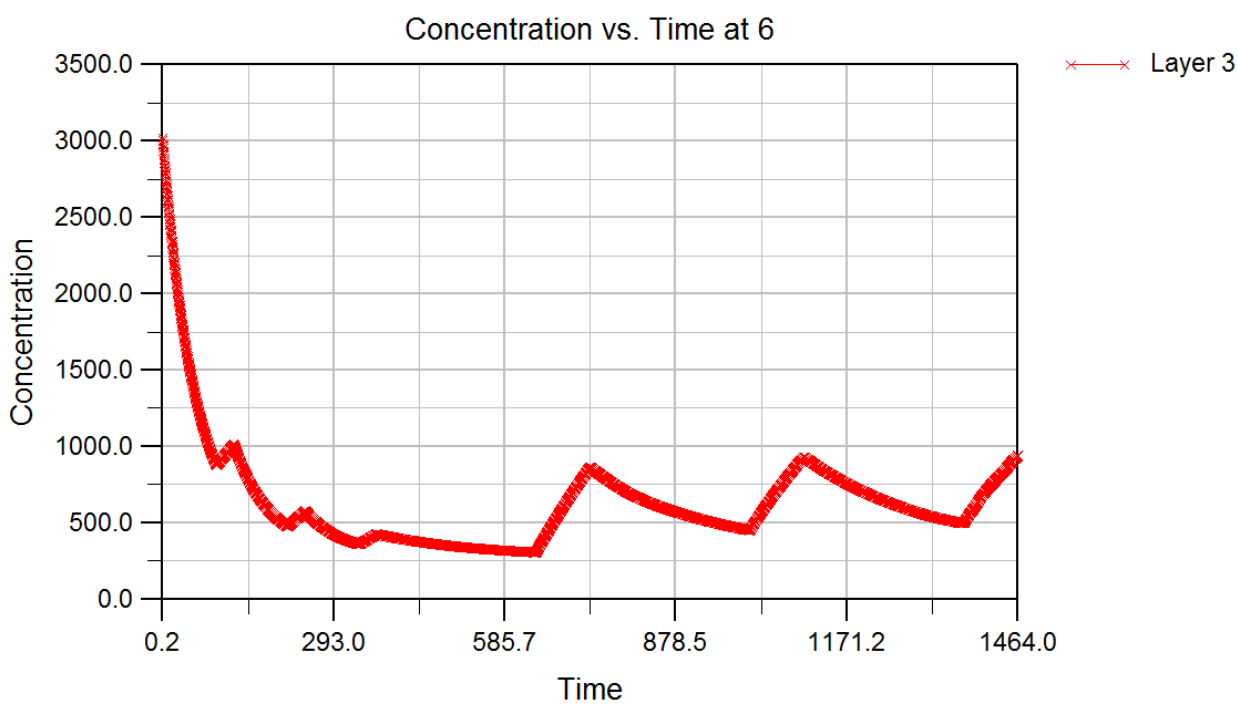


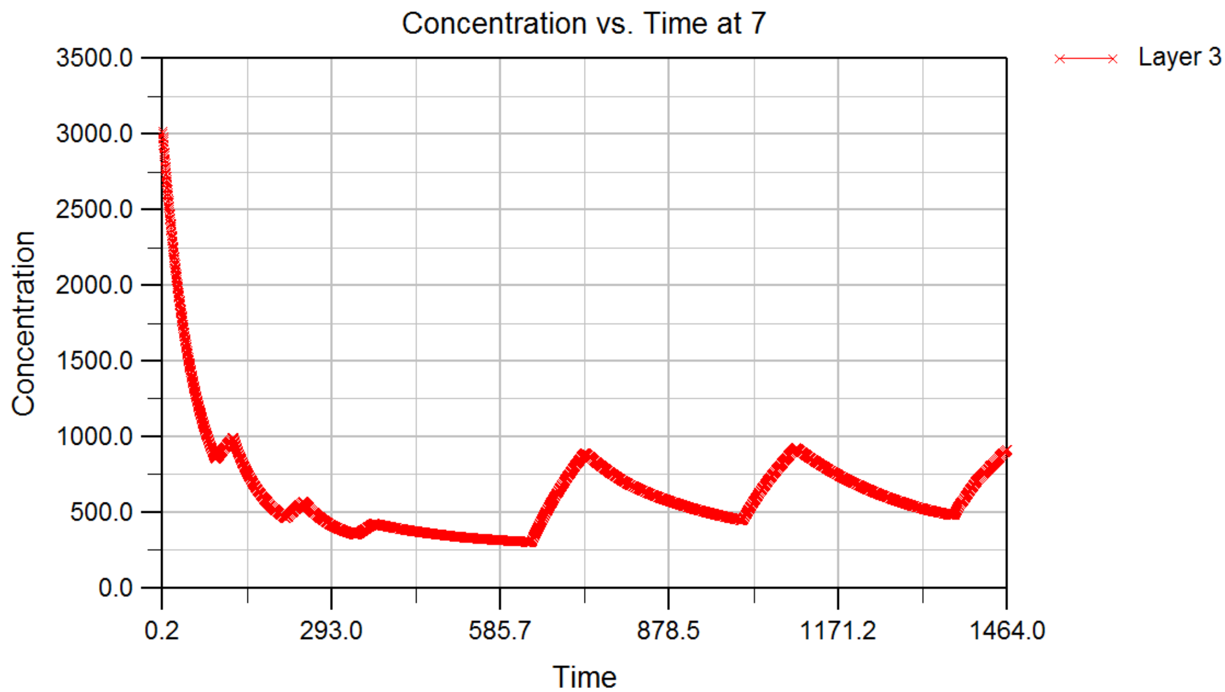
Concentration vs. Time at 2
Layer 3
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
Concentration
0.2
293.0
585.7
878.5
1171.2
1464.0
Time

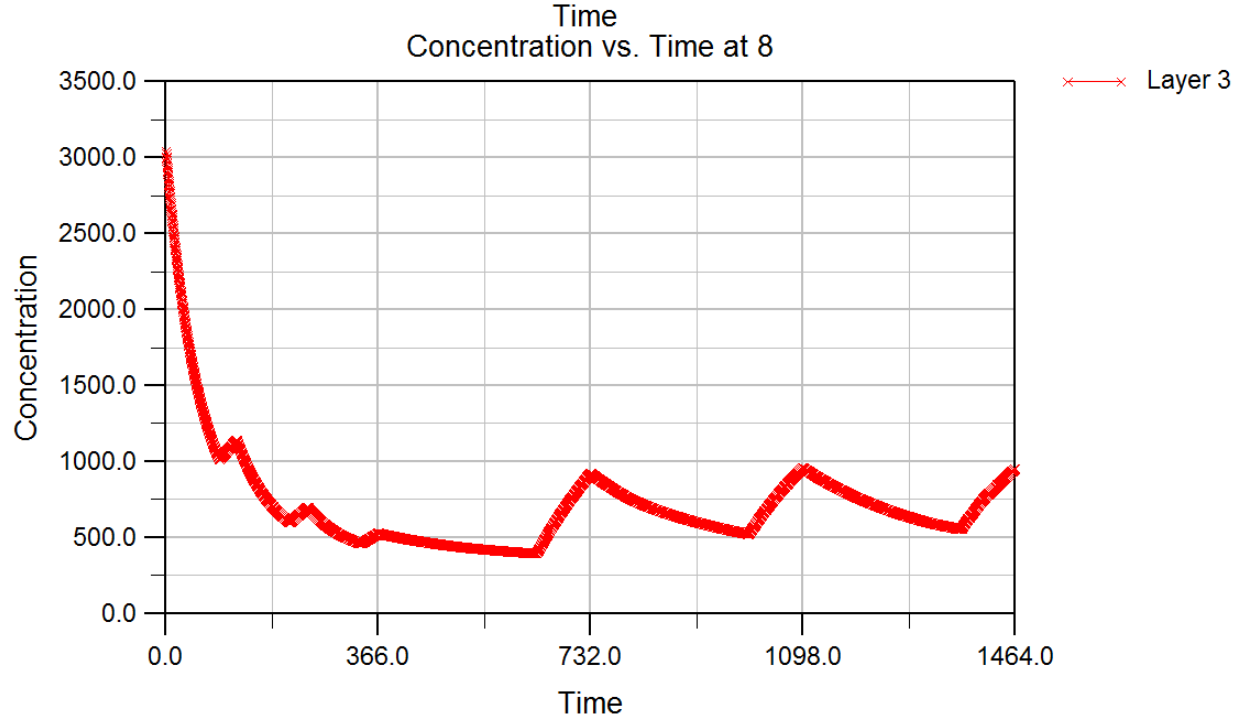

Concentration vs. Time at 3
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.2
293.0
585.7
878.5
1171.2
1464.0
Time


Concentration vs. Time at 4
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.2
293.0
585.7
878.5
1171.2
1464.0
Time


Concentration vs. Time at 5
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.2
293.0
585.7
878.5
1171.2
1464.0
Time

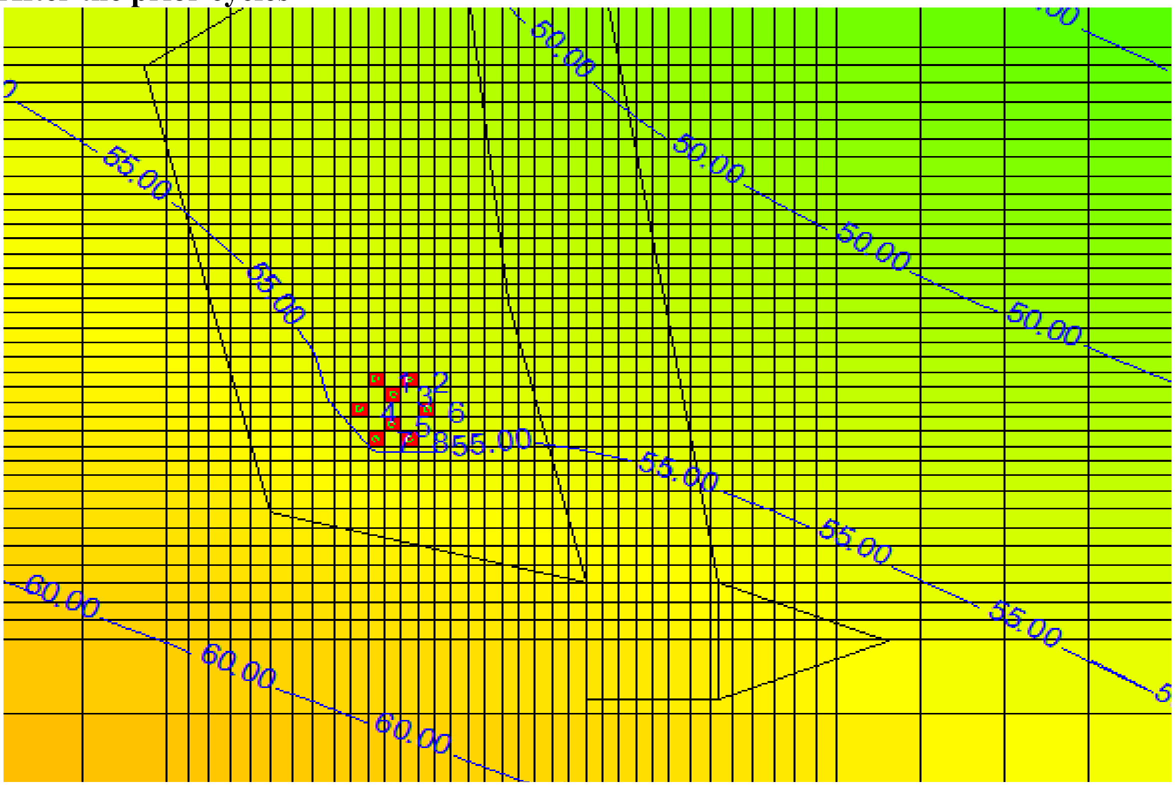

Concentration vs. Time at 6
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.2
293.0
585.7
878.5
1171.2
1464.0
Time


Concentration vs. Time at 7
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.2
293.0
585.7
878.5
1171.2
1464.0
Time

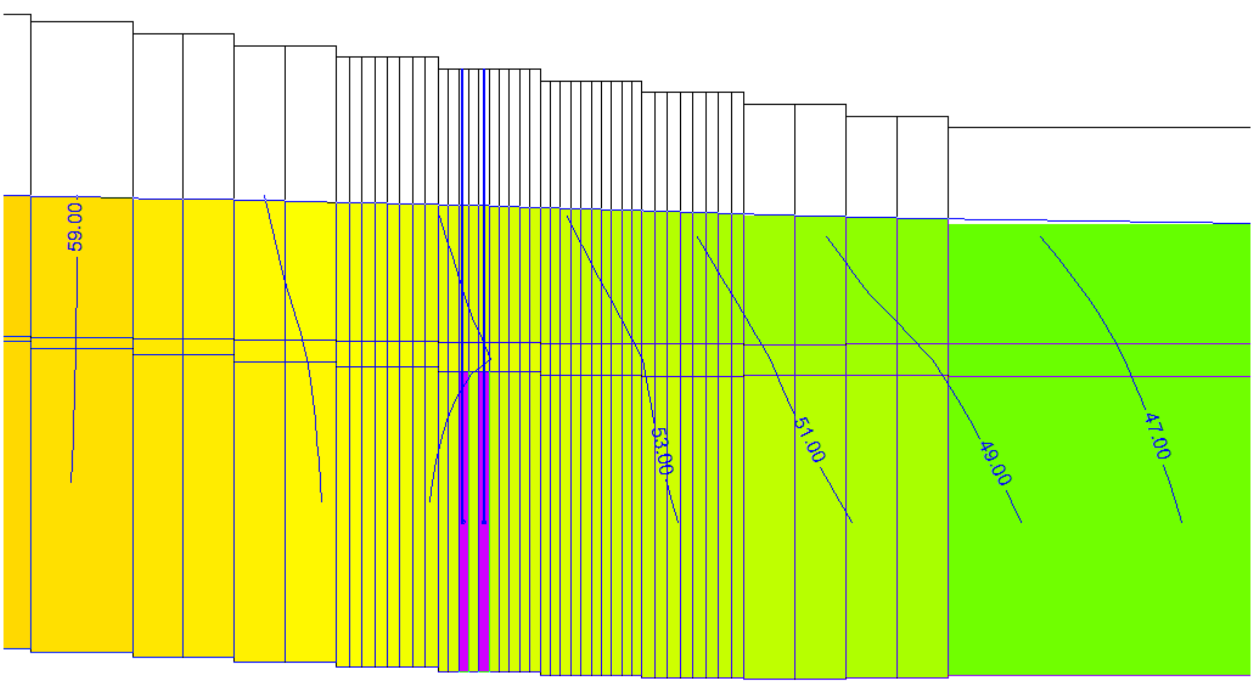

Concentration vs. Time at 8
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time

Run4 MODFLOW

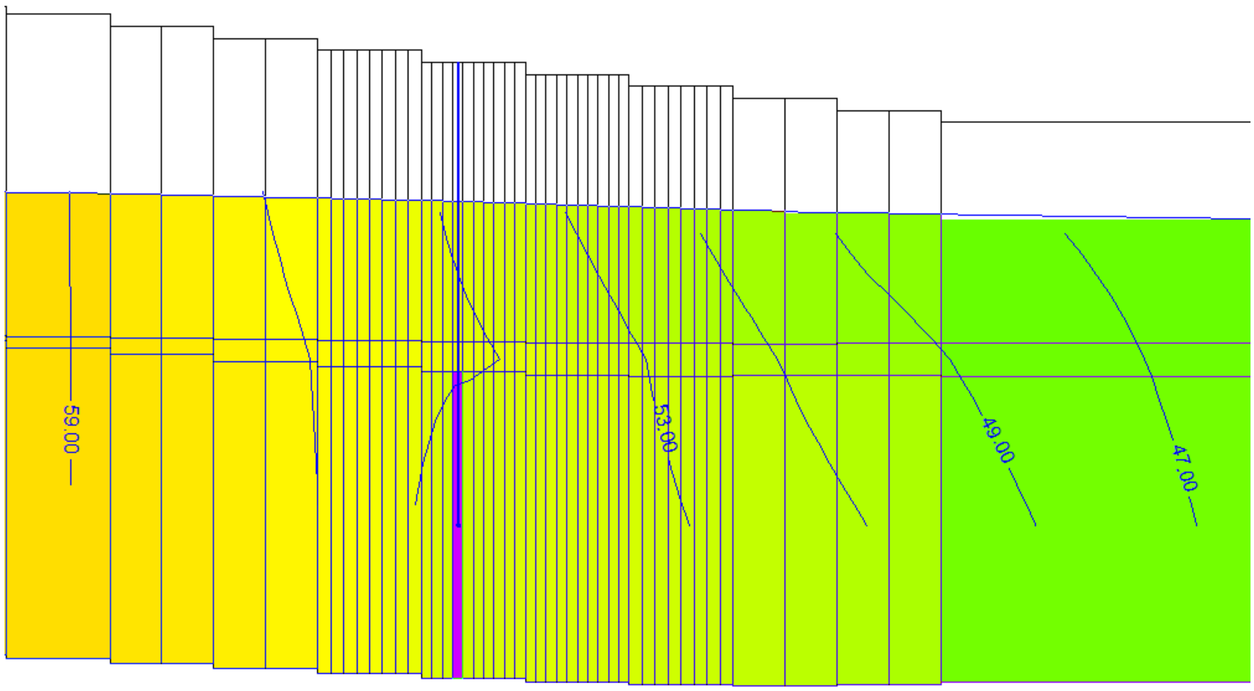
After the prior cycles



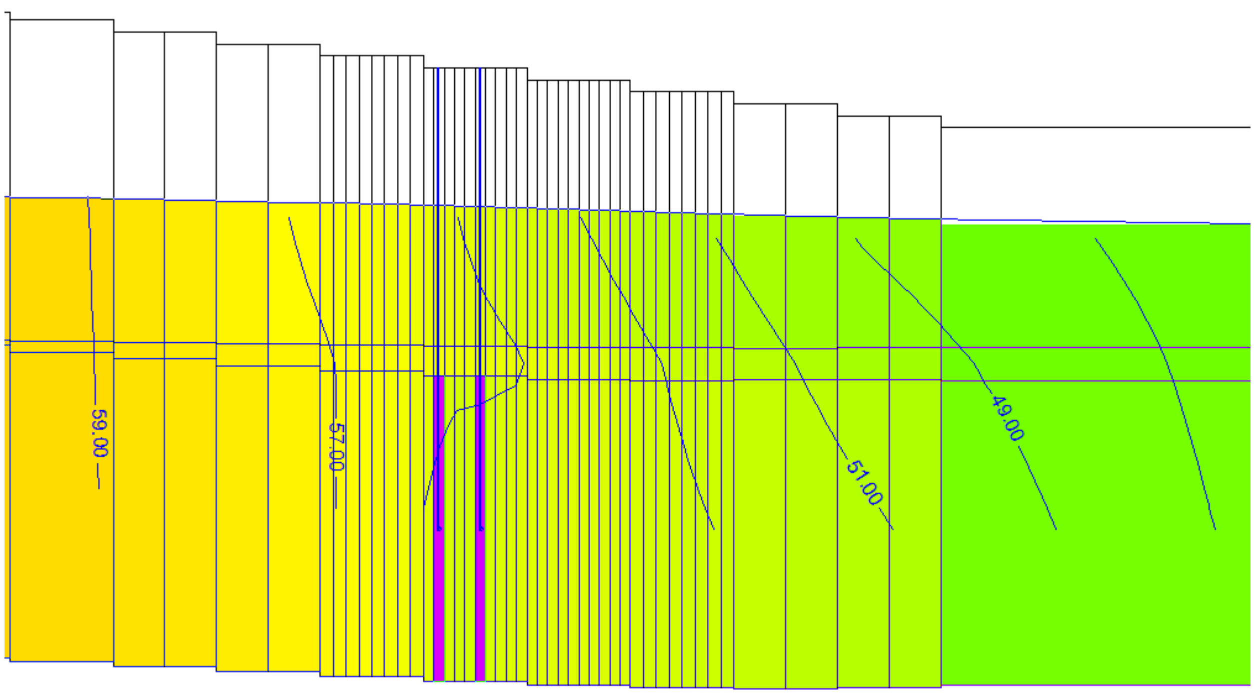
Cross-Section along Row 26



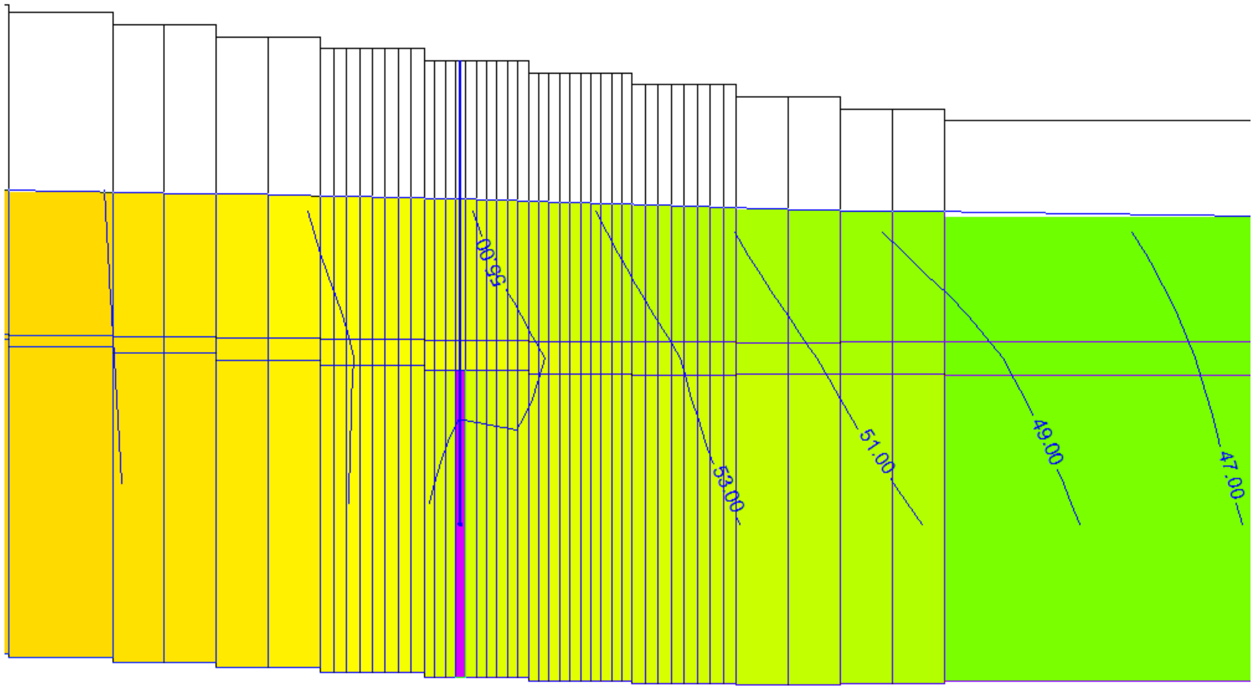
Cross-Section along Row 27



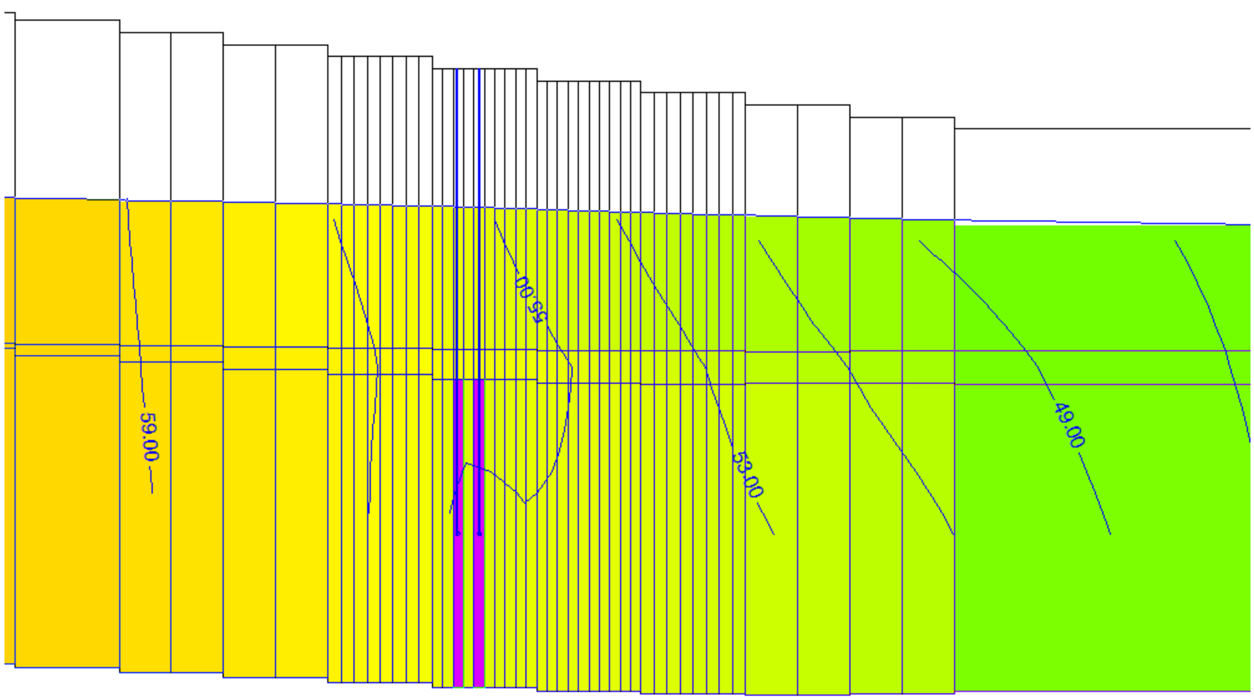
Cross-Section along Row 28



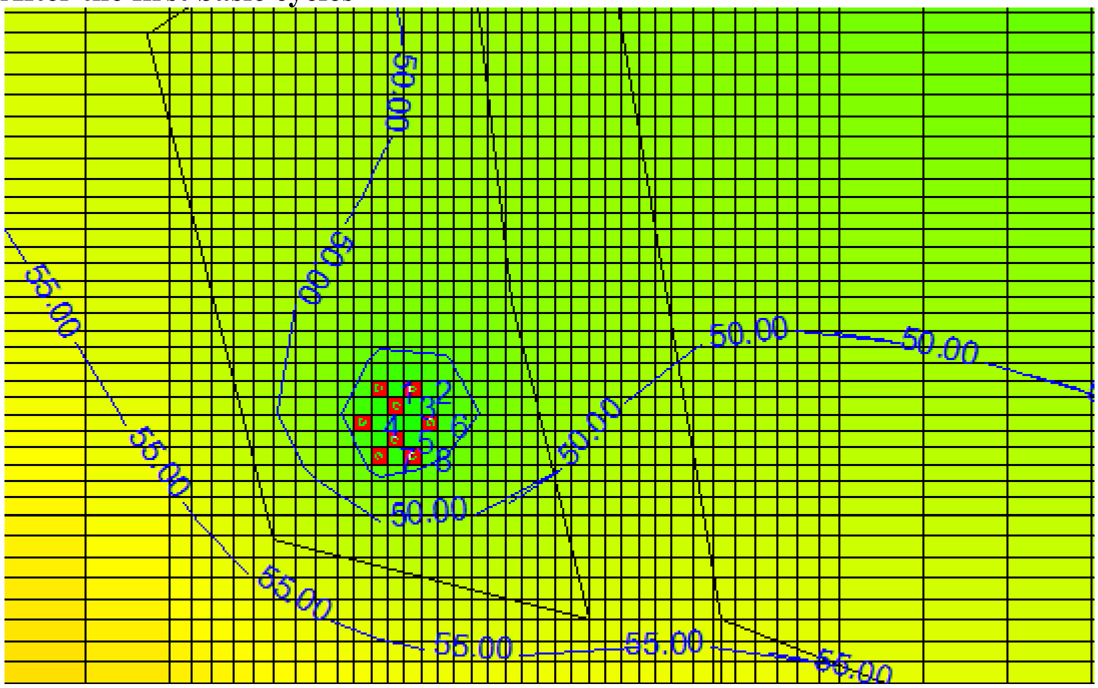
Cross-Section along Row 29



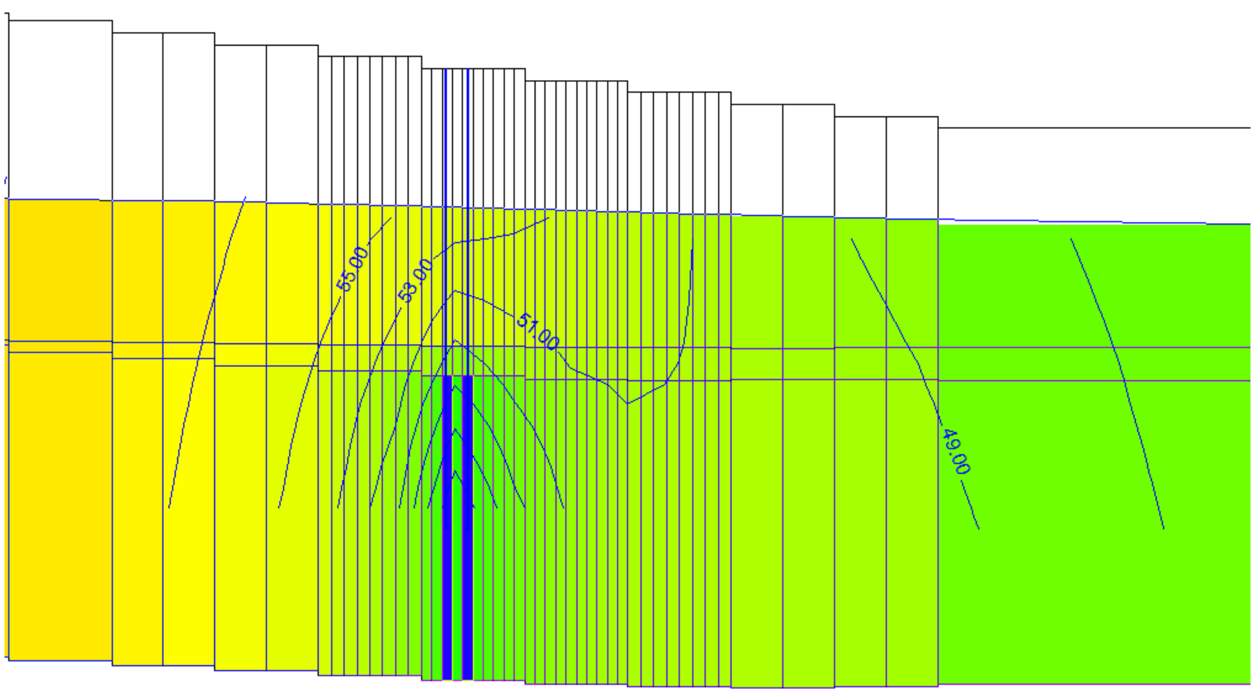
Cross-Section along Row 30



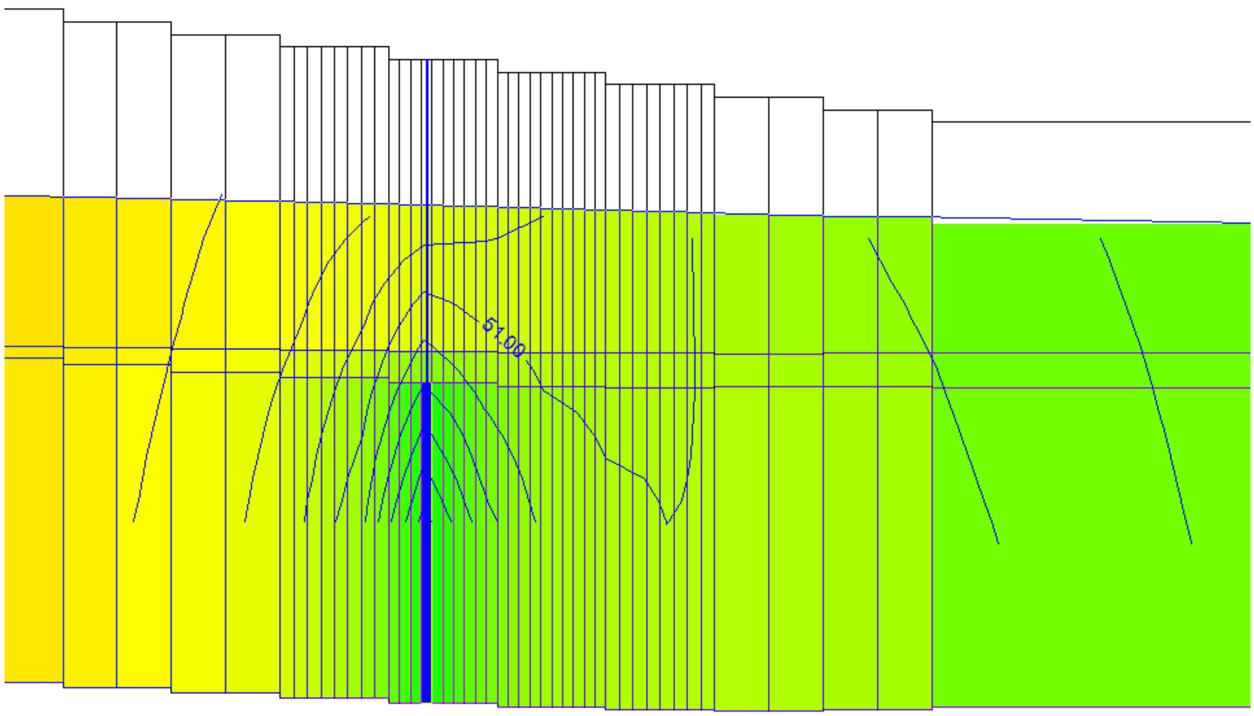
After the first basic cycles



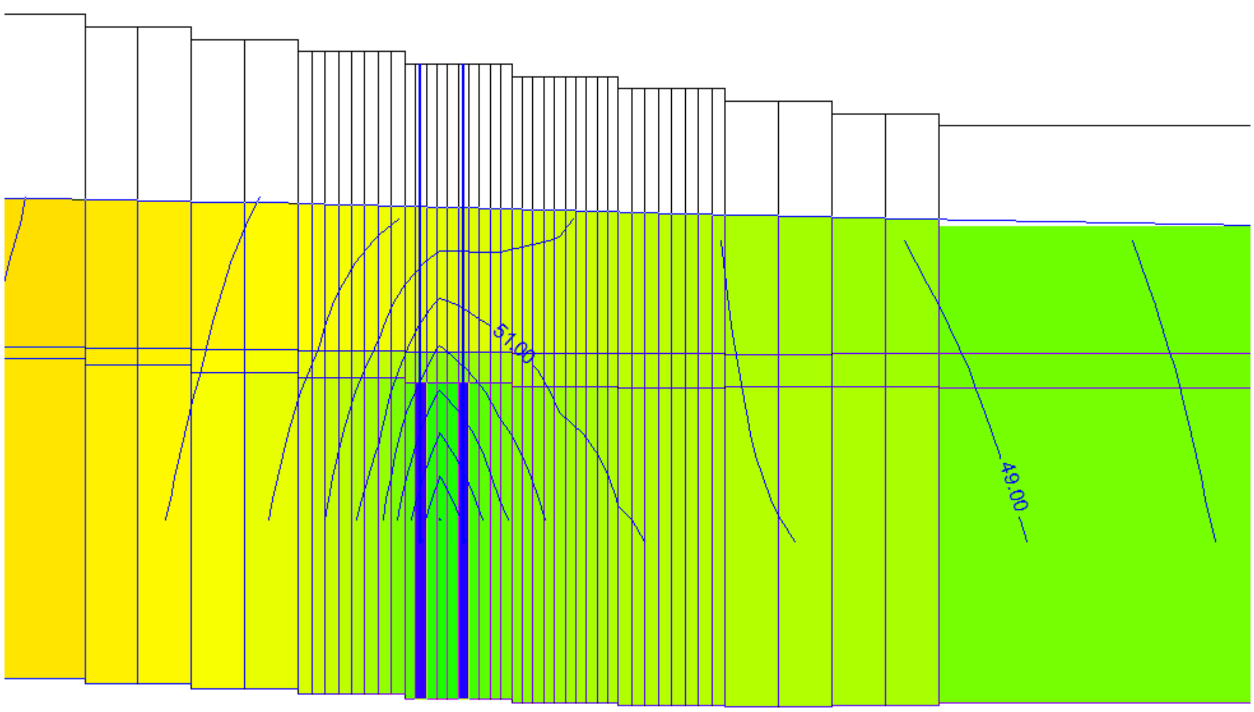
Cross-Section along Row 26



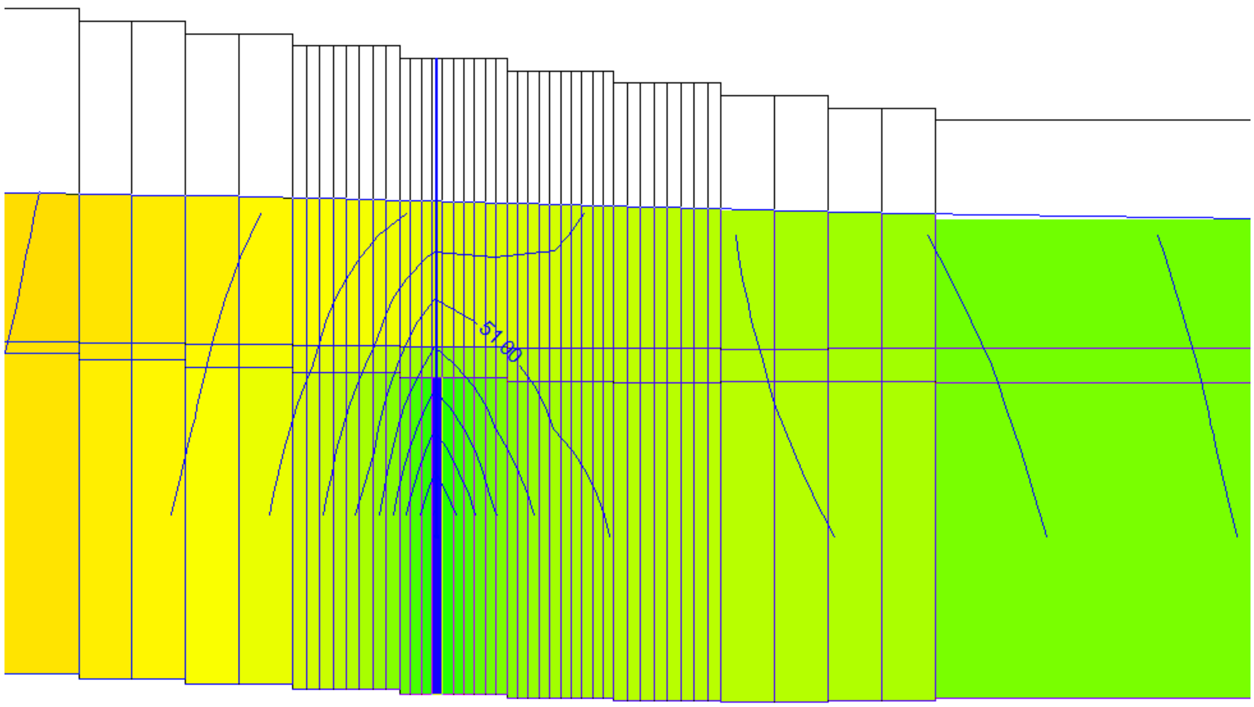
Cross-Section along Row 27



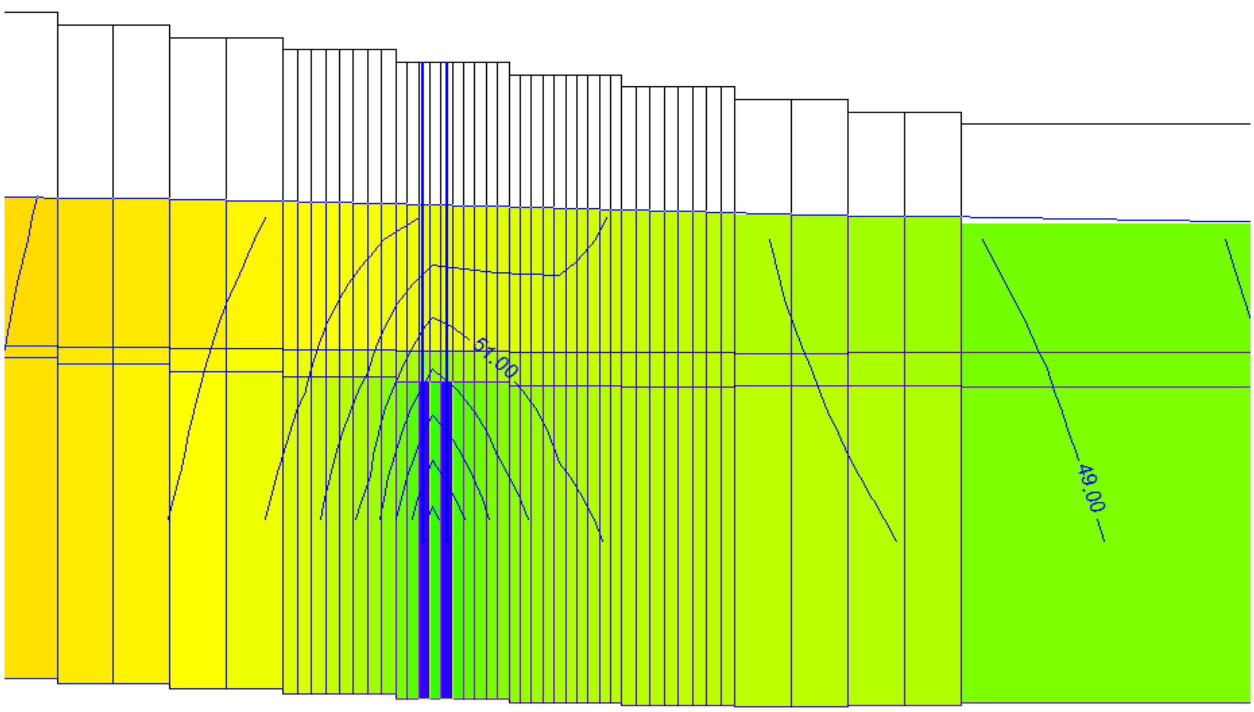
Cross-Section along Row 28



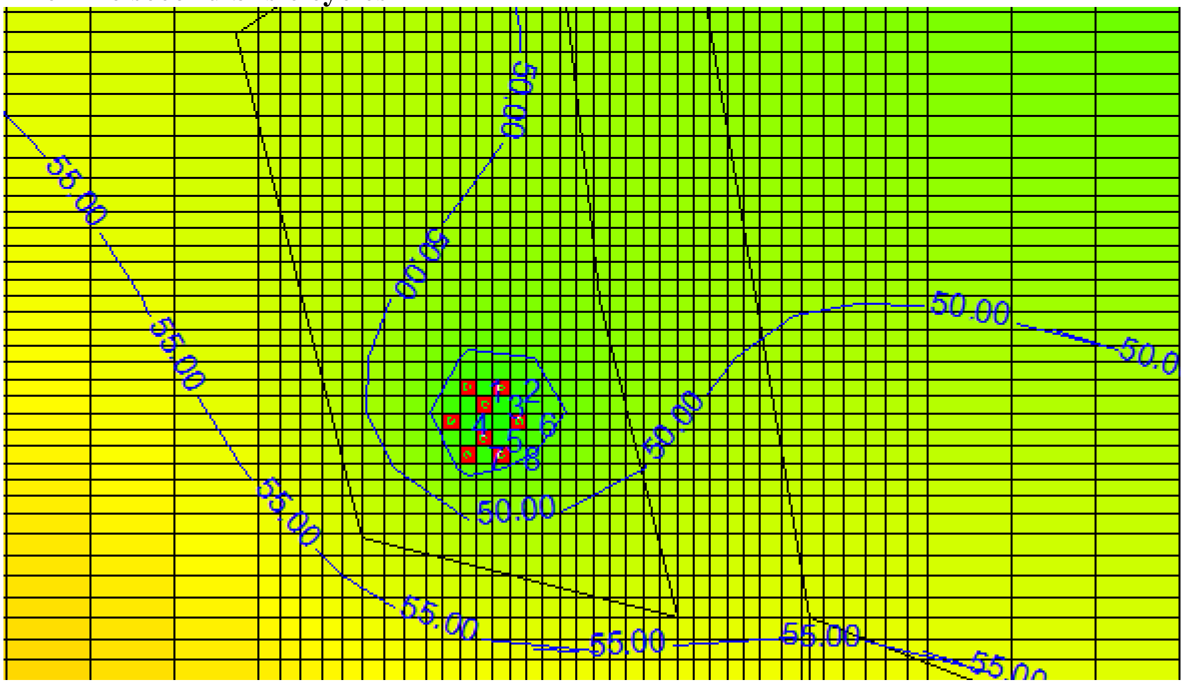
Cross-Section along Row 29



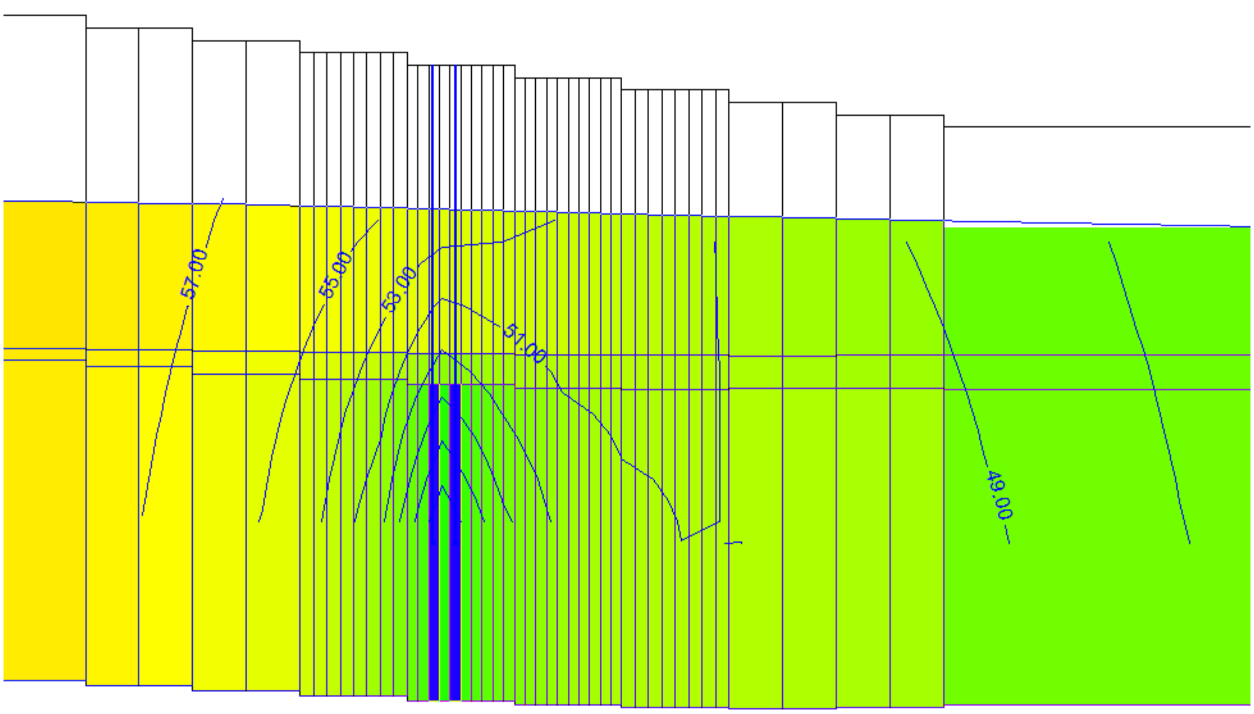
Cross-Section along Row 30



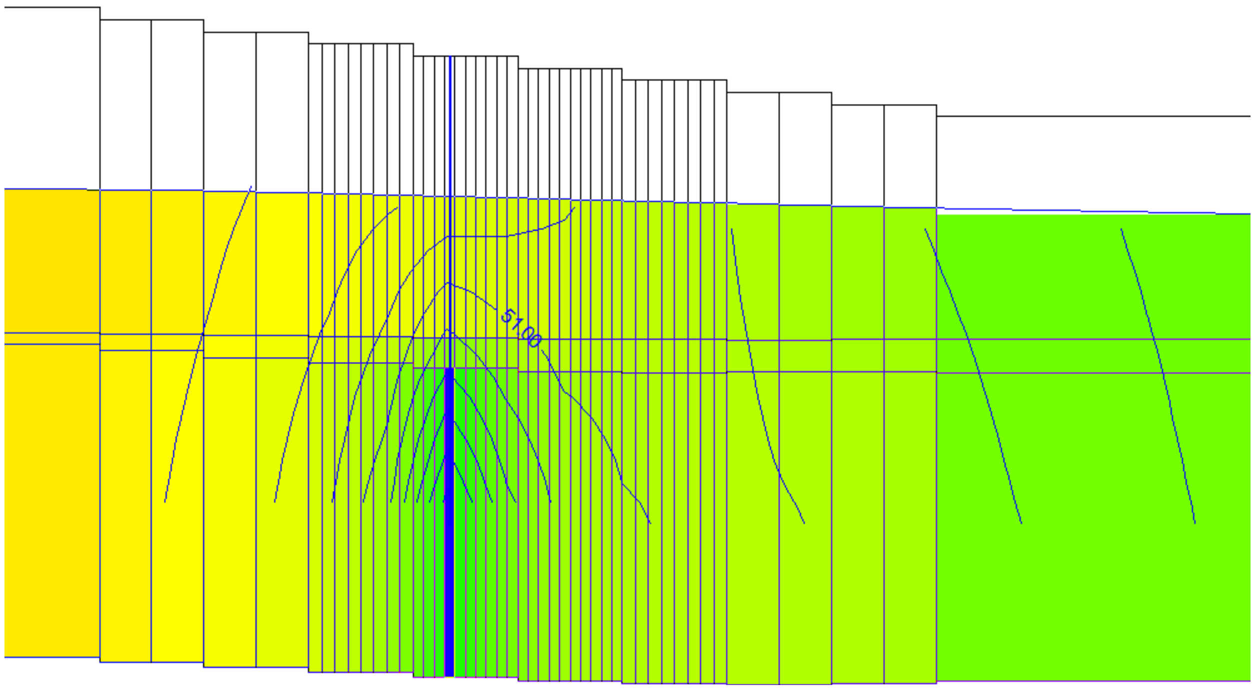
After the second basic cycles



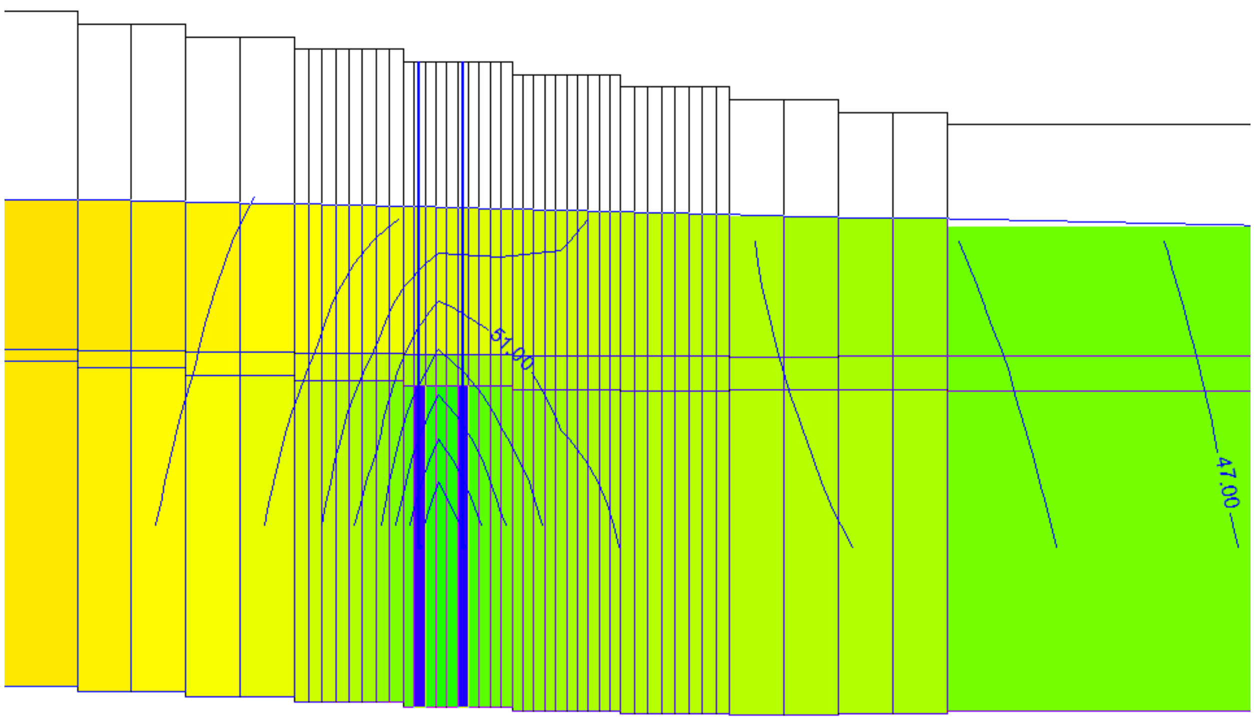
Cross-Section along Row 26



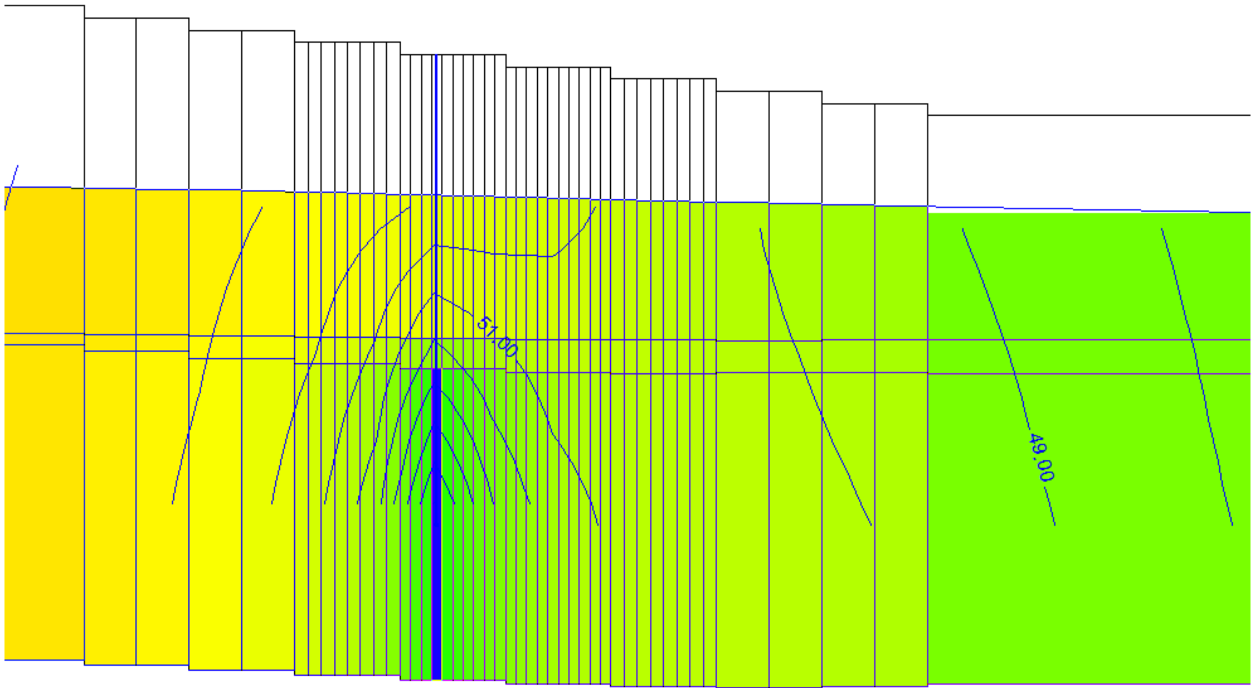
Cross-Section along Row 27



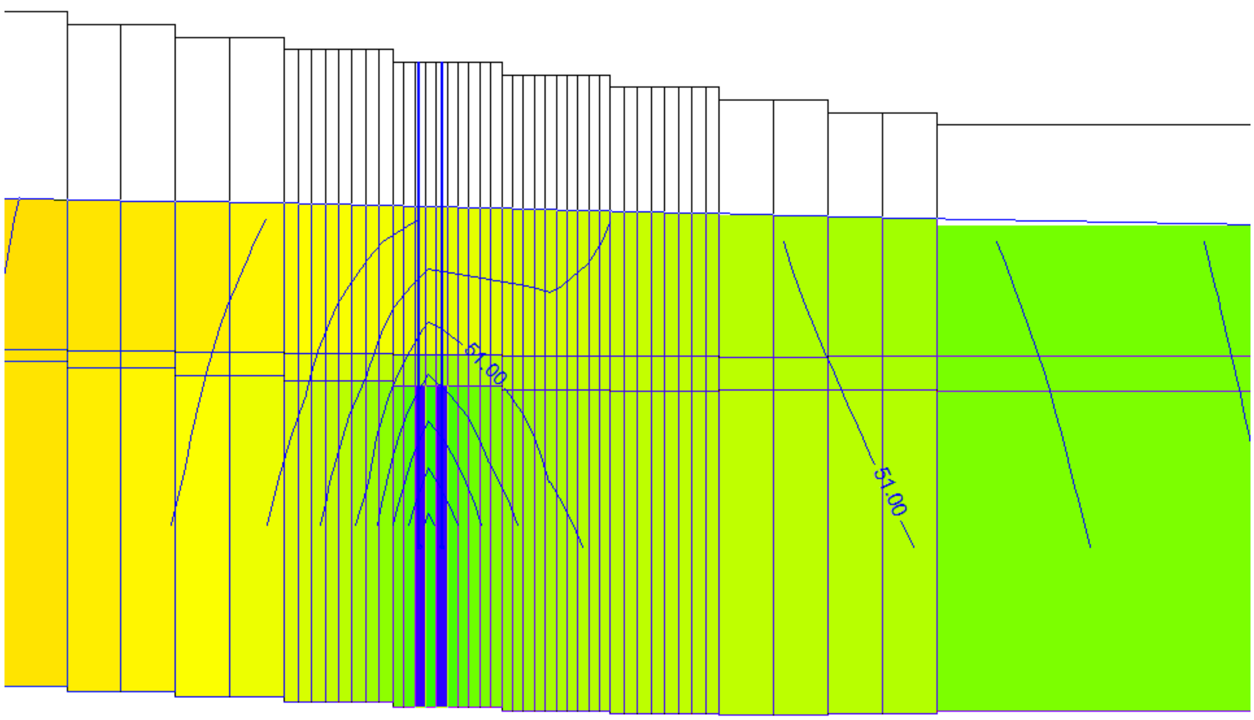
Cross-Section along Row 28



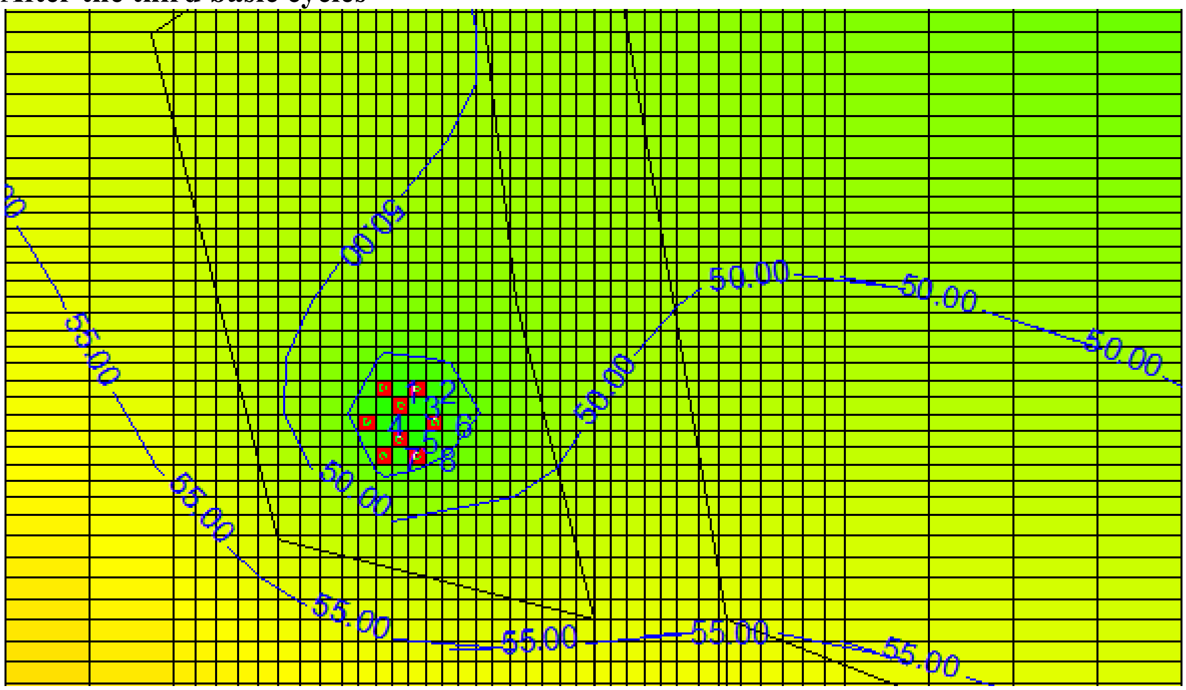
Cross-Section along Row 29



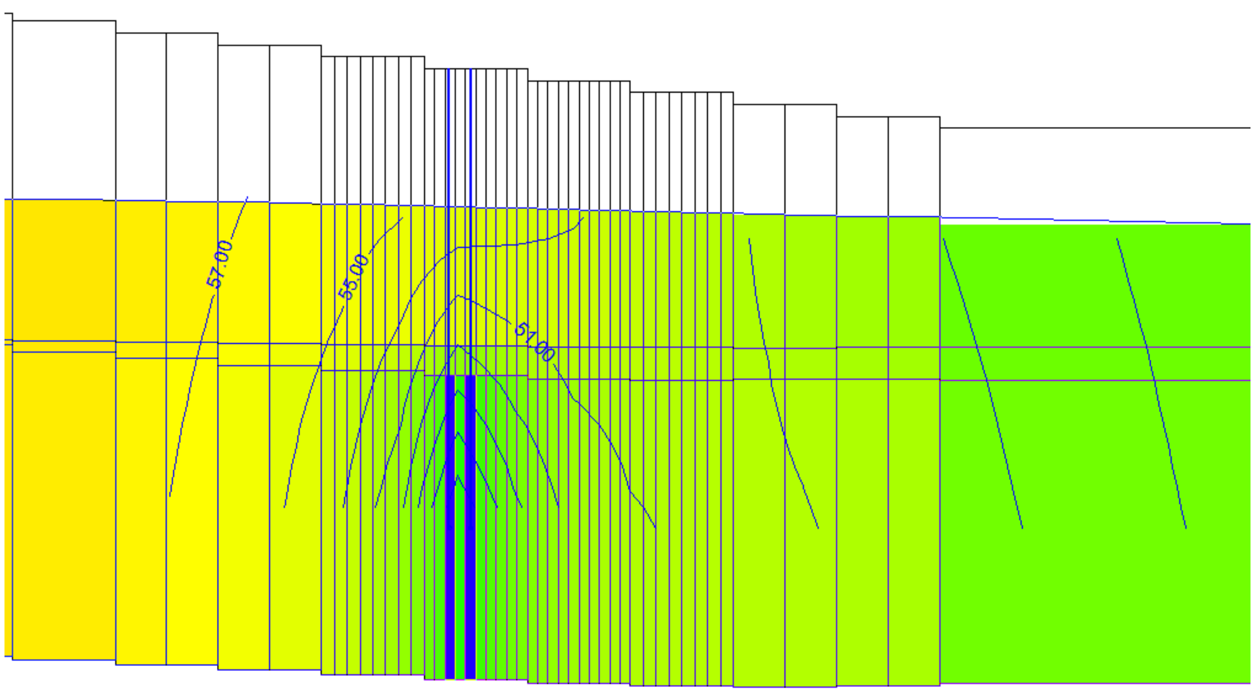
Cross-Section along Row 30



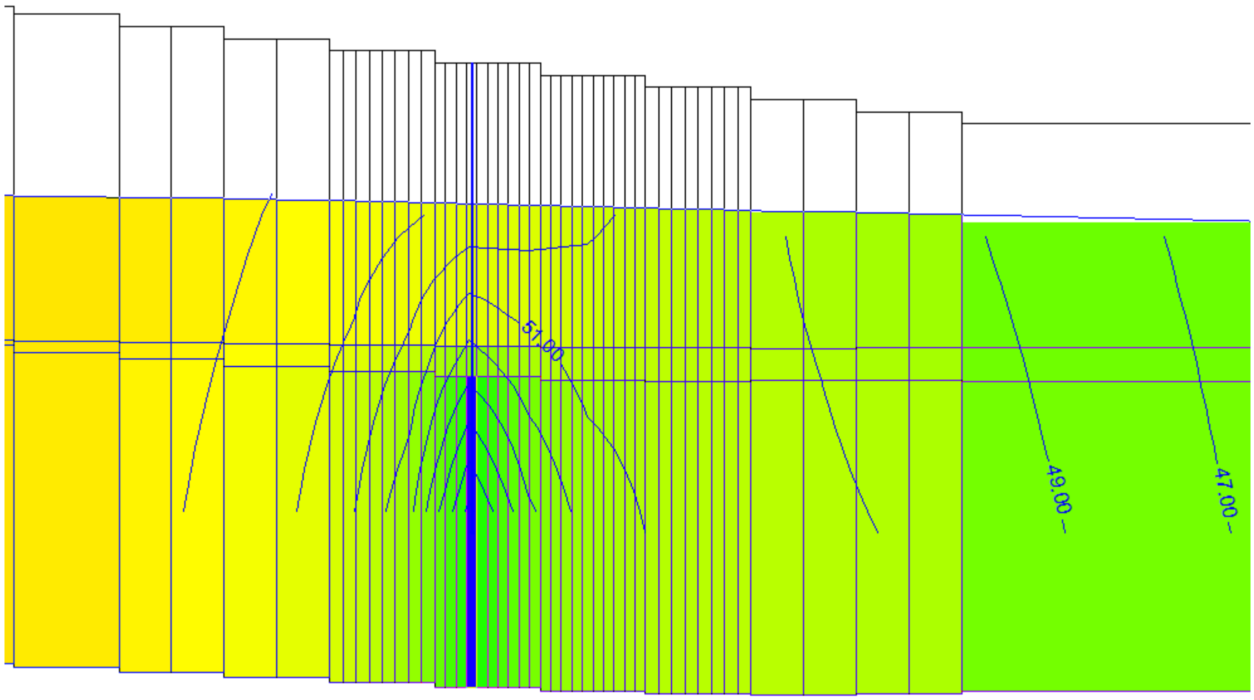
After the third basic cycles



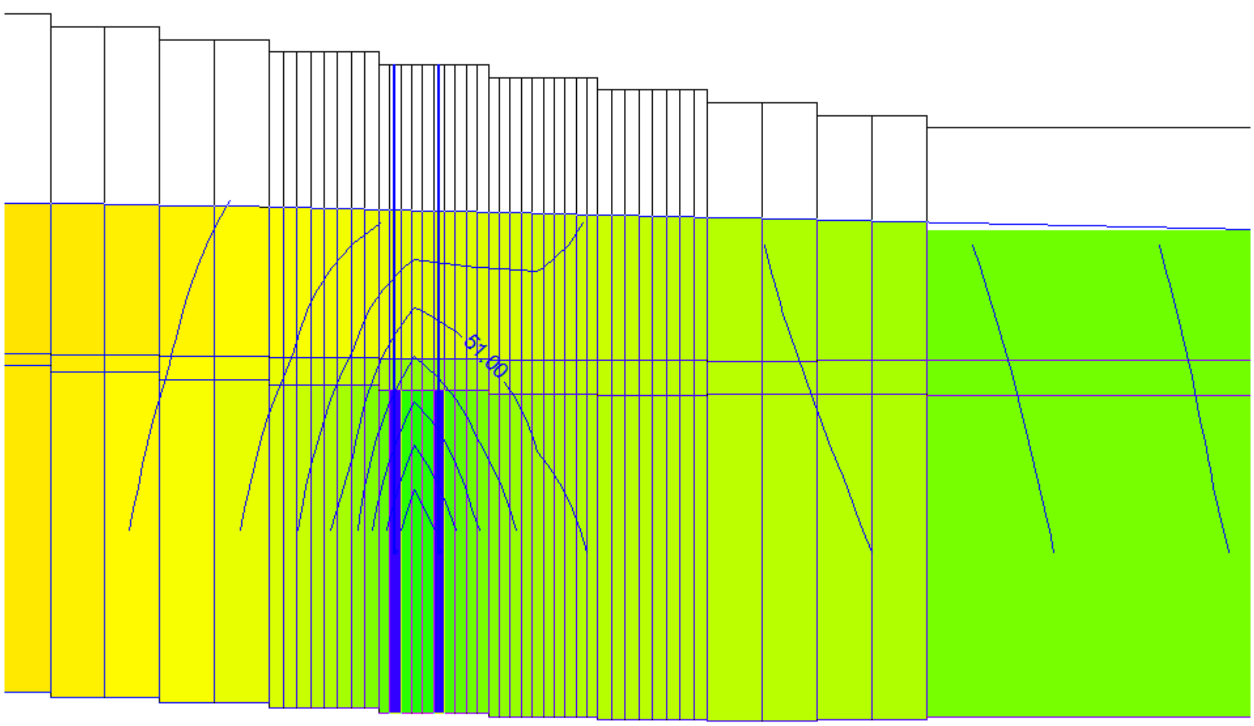
Cross-Section along Row 26



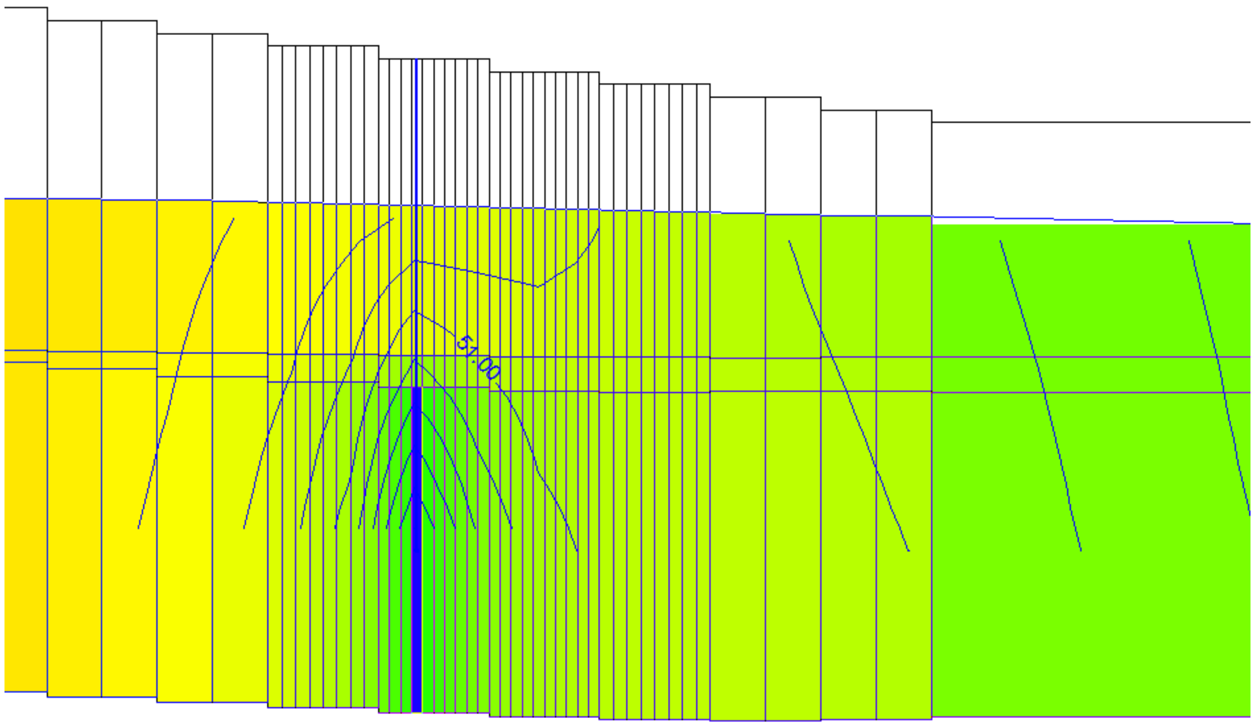
Cross-Section along Row 27



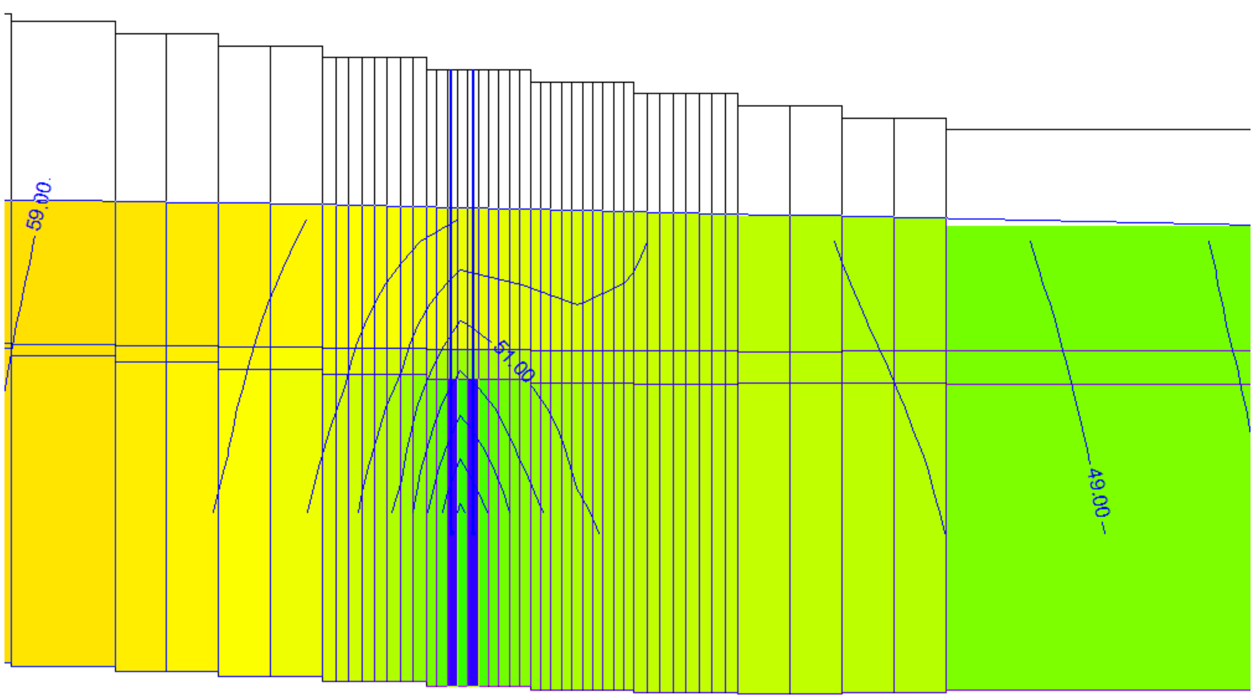
Cross-Section along Row 28

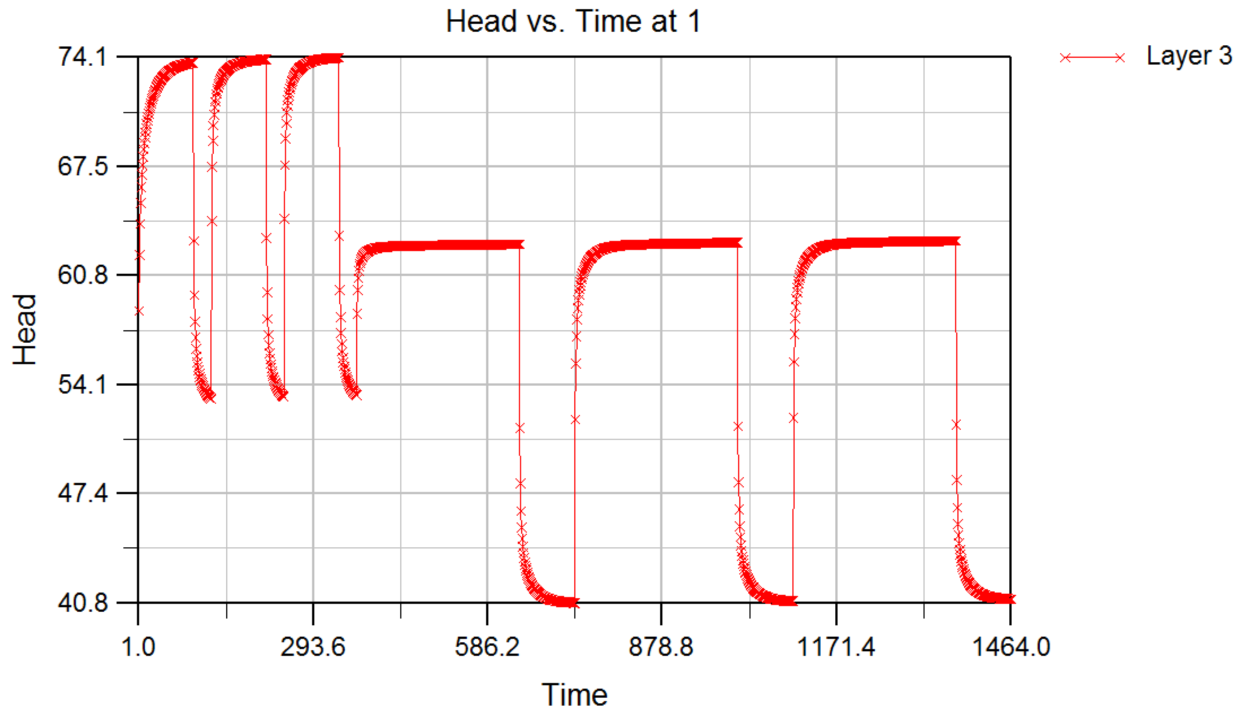


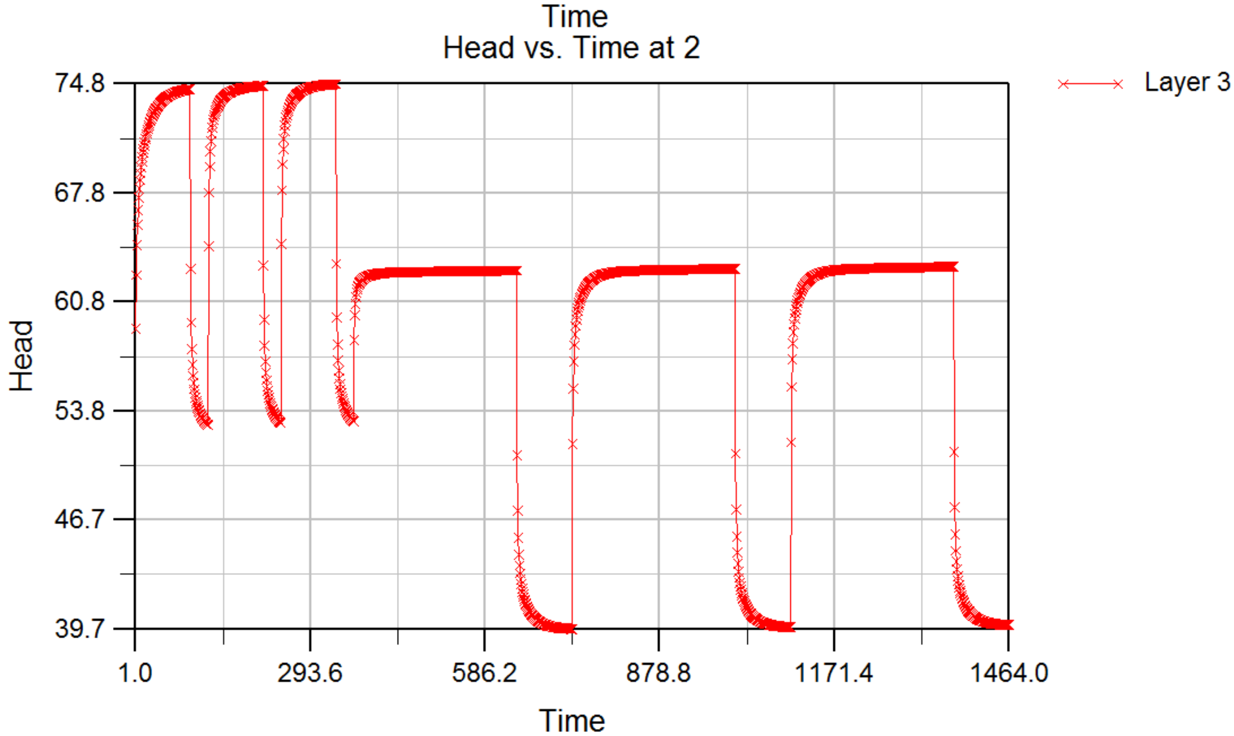
Cross-Section along Row 29

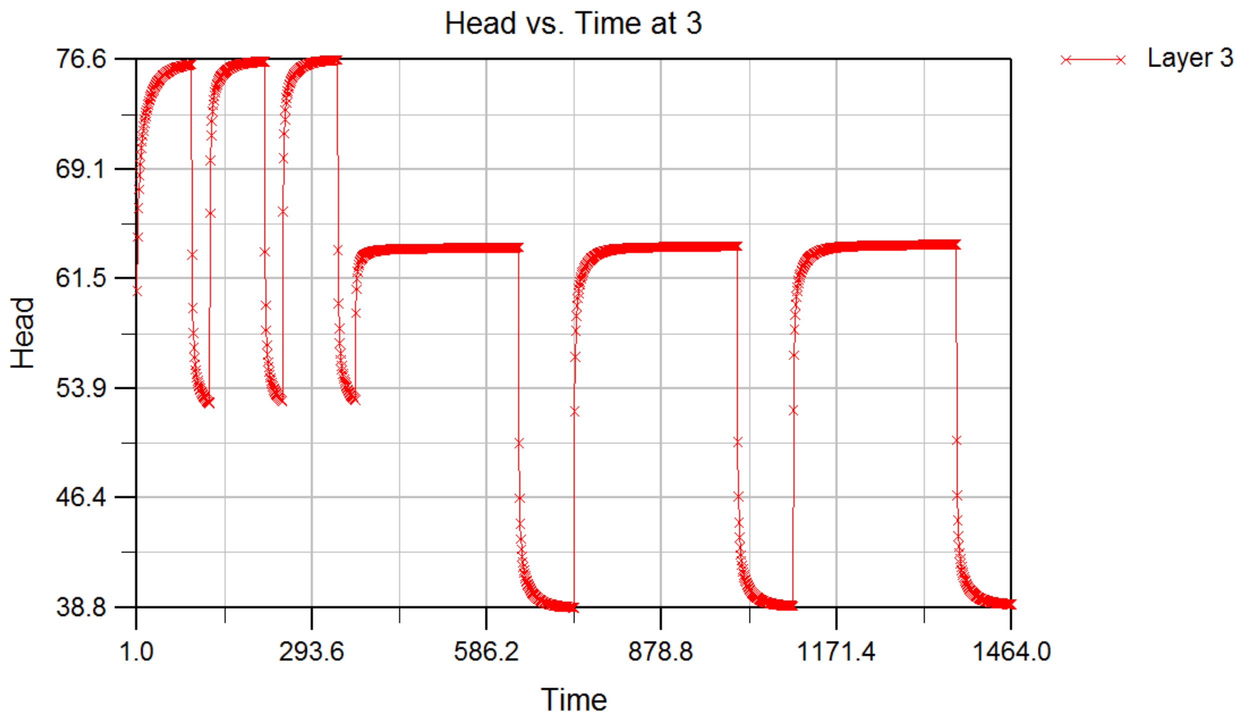


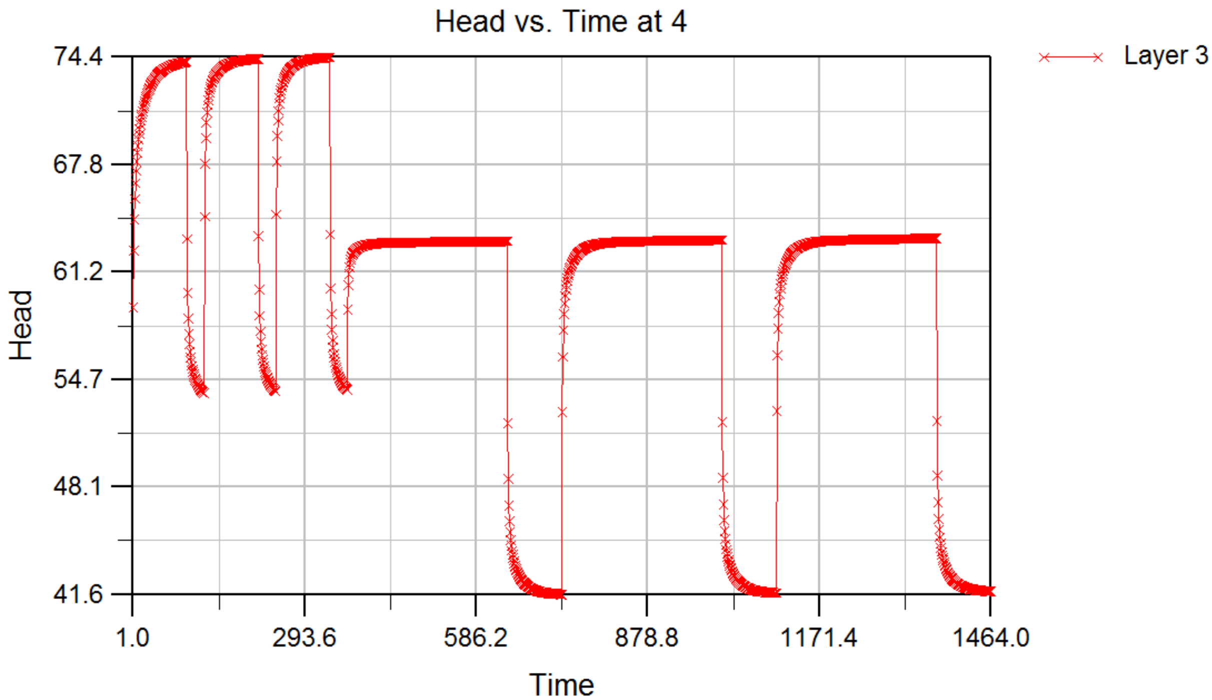
Cross-Section along Row 30

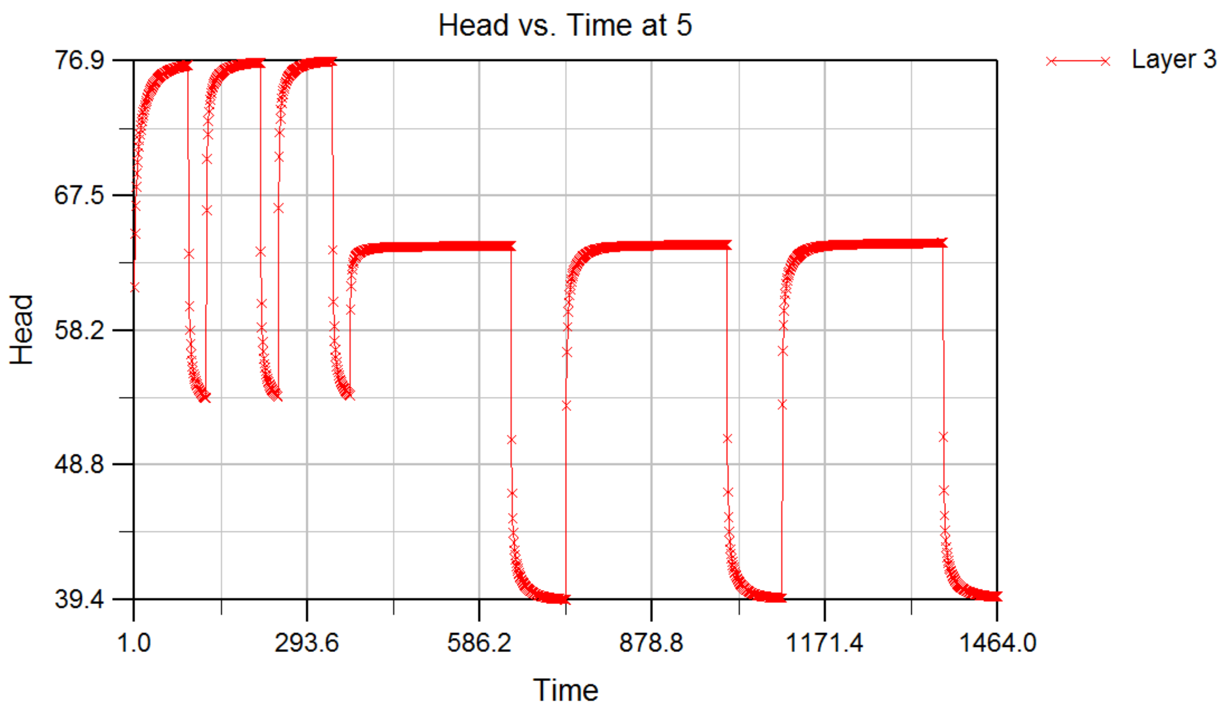


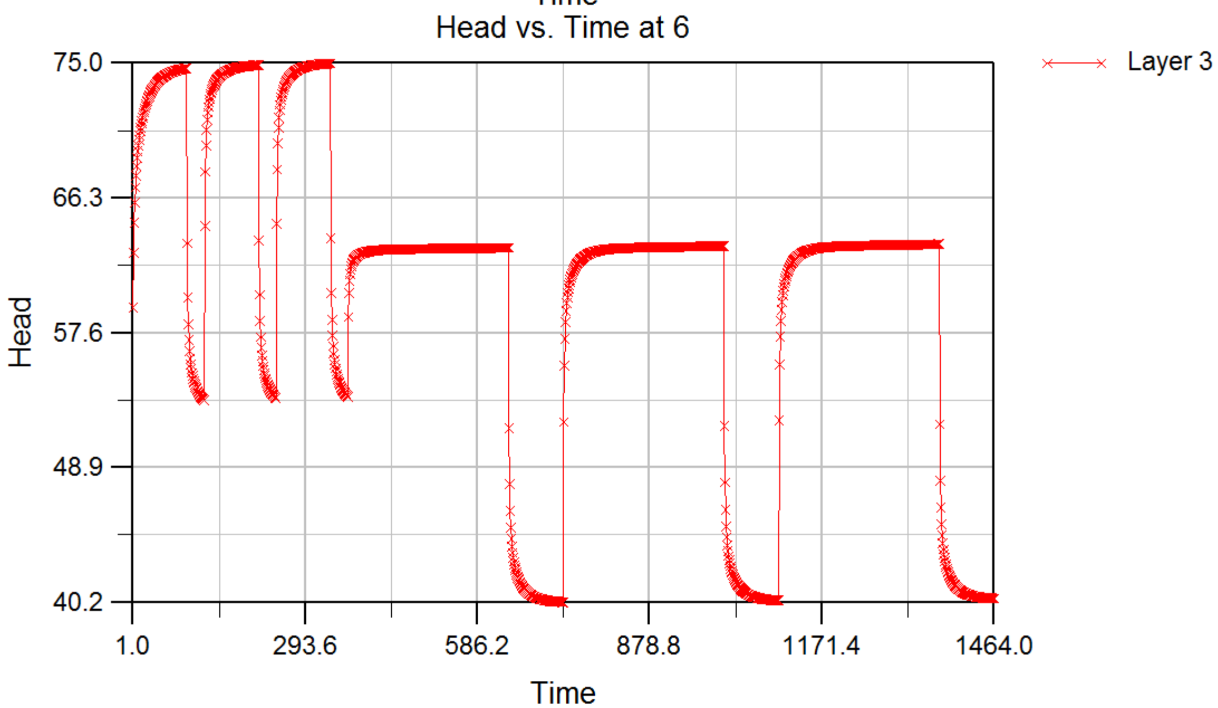

Head vs. Time at 1
Layer 3
74.1
67.5
60.8
54.1
47.4
40.8
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

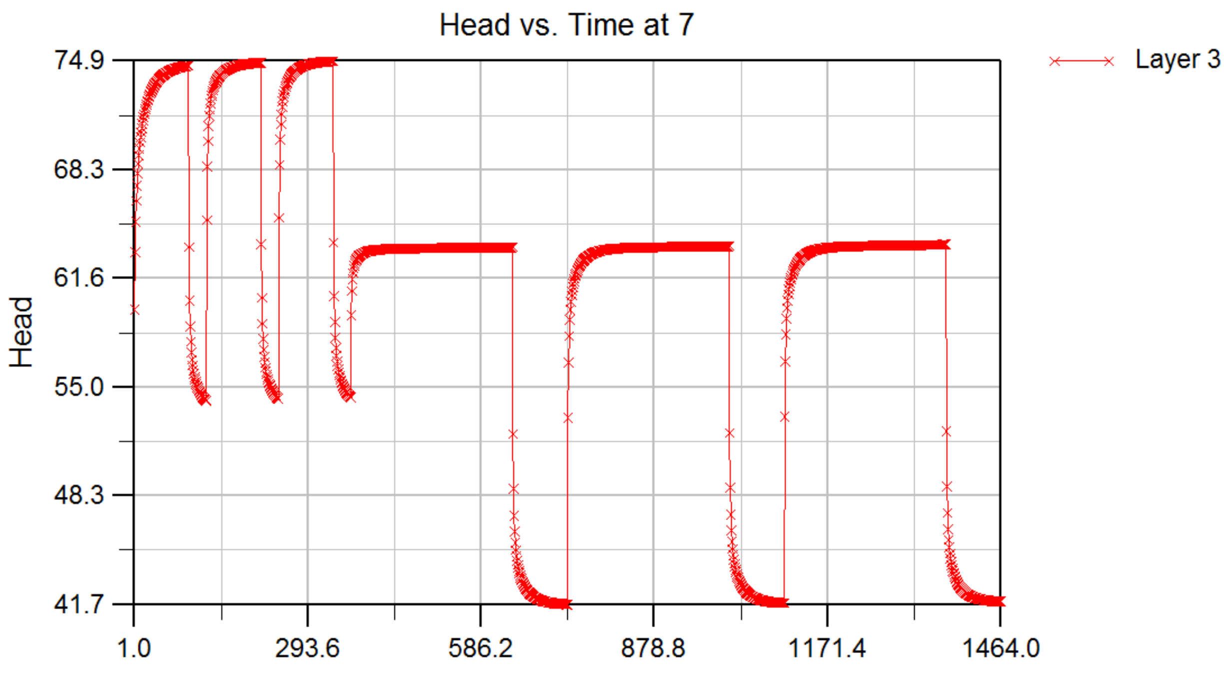

Head vs. Time at 2
Layer 3
74.8
67.8
60.8
53.8
46.7
39.7
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

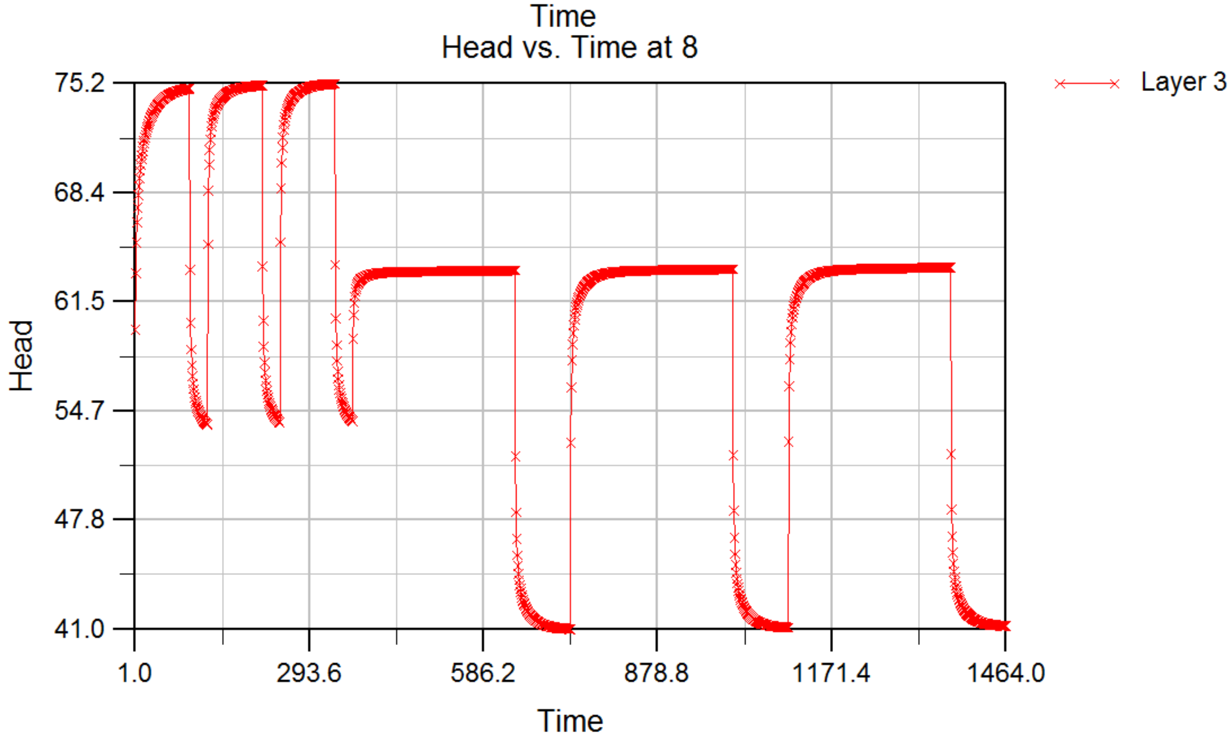

Head vs. Time at 3
Layer 3
76.6
69.1
61.5
53.9
46.4
38.8
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time


Head vs. Time at 4
Layer 3
74.4
67.8
61.2
54.7
48.1
41.6
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time


Head vs. Time at 5
Layer 3
Head
76.9
67.5
58.2
48.8
39.4
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

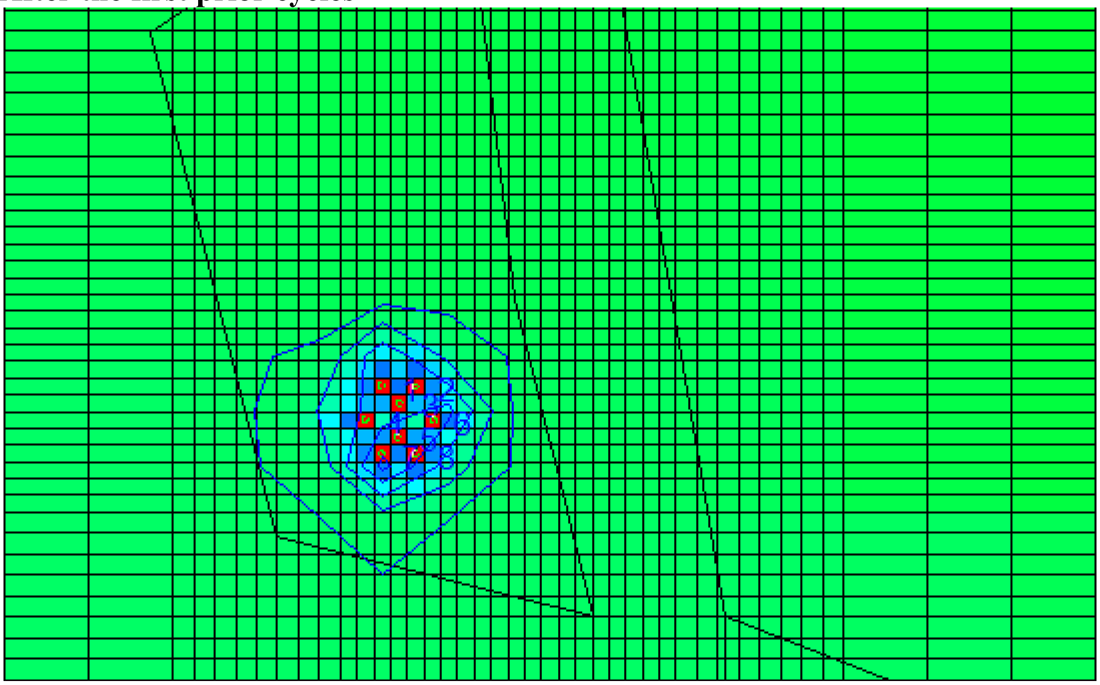

Head vs. Time at 6
Layer 3
Head
75.0
66.3
57.6
48.9
40.2
1.0
293.6
586.2
878.8
1171.4
1464.0
Time


Head vs. Time at 7
Layer 3
74.9
68.3
61.6
55.0
48.3
41.7
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

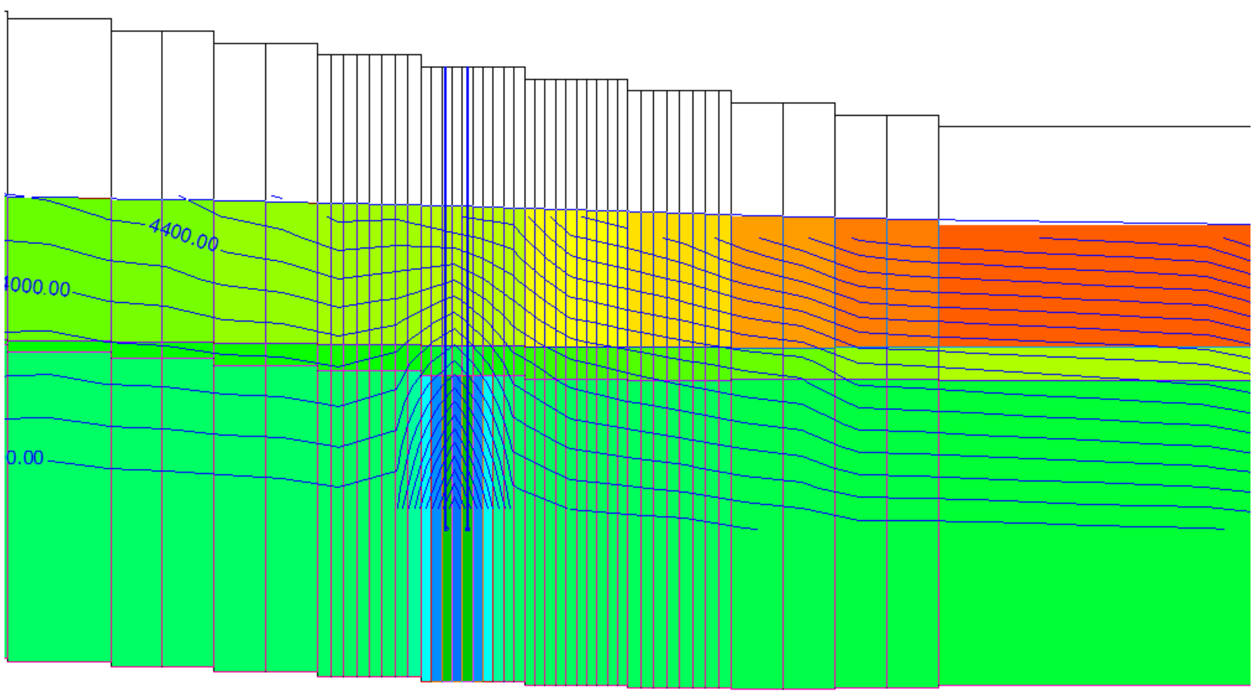

Head vs. Time at 8
Layer 3
75.2
68.4
61.5
54.7
47.8
41.0
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

RUN 4 MT3D

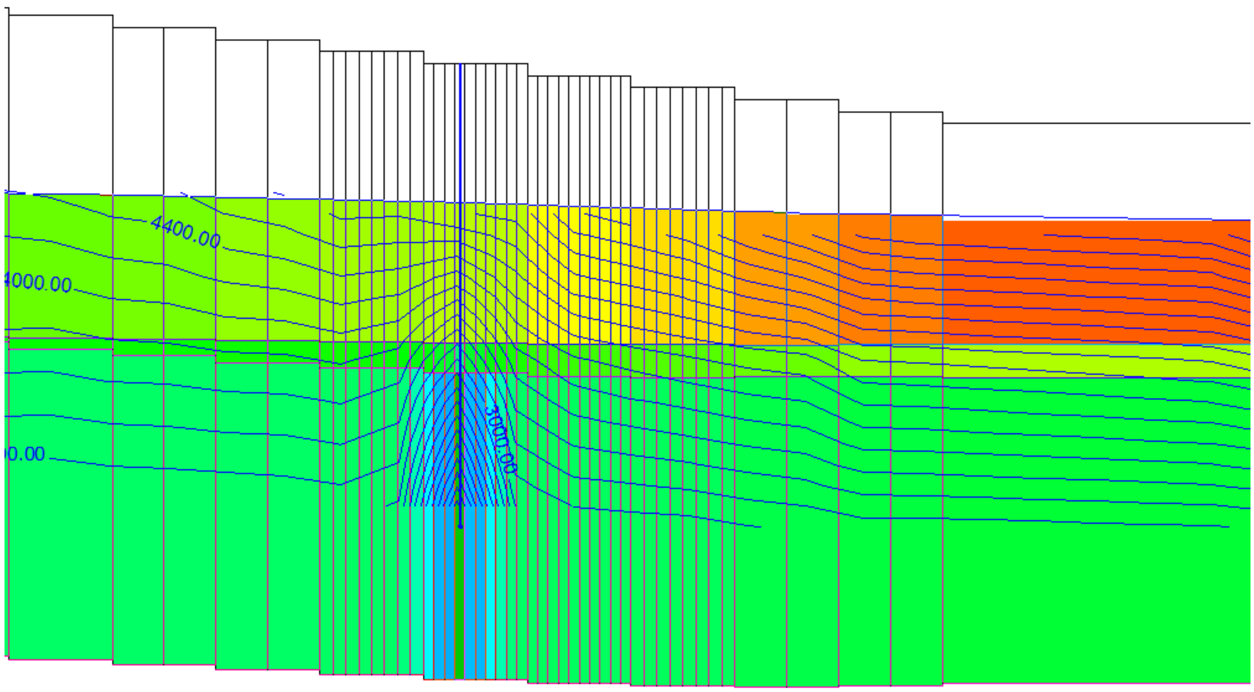
After the first prior cycles



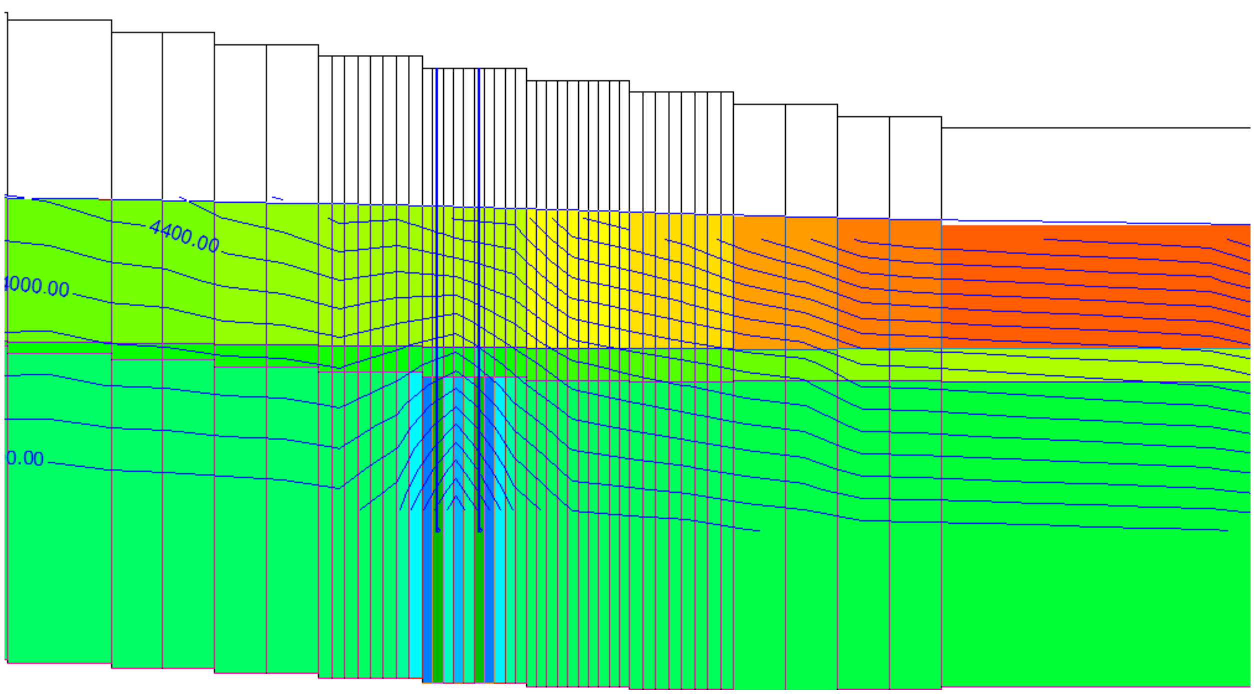
Cross-Section along Row 26



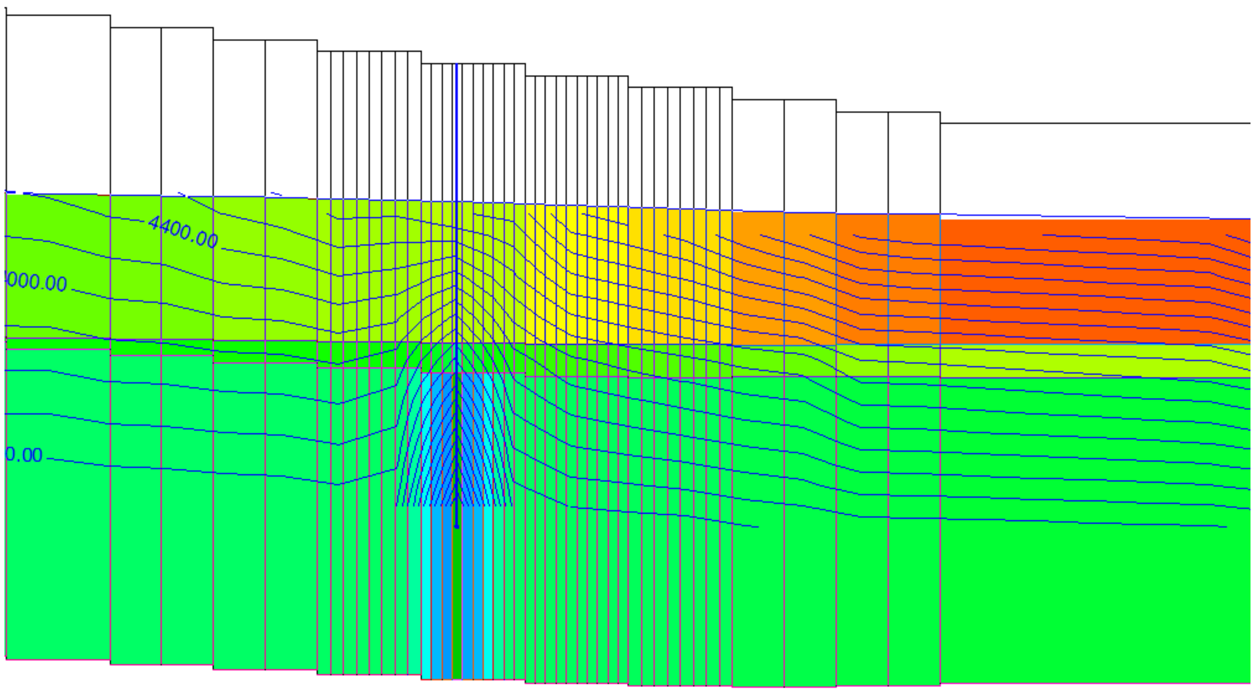
Cross-Section along Row 27



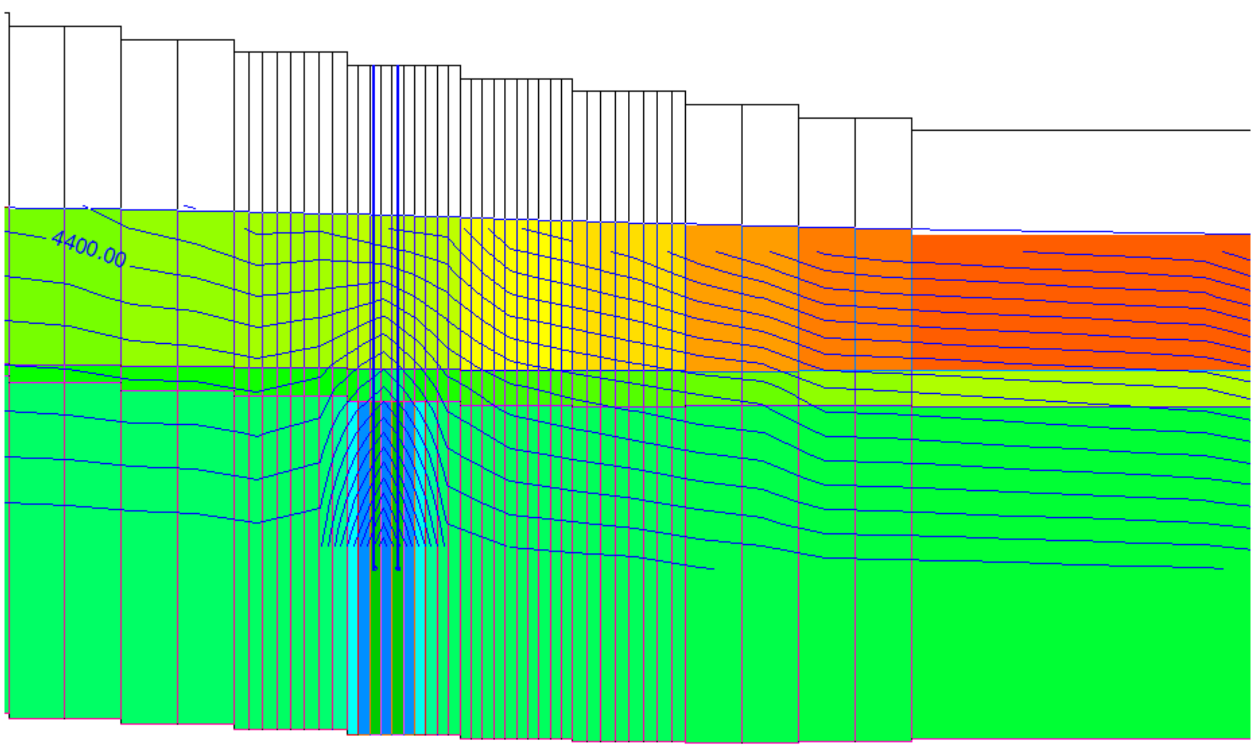
Cross-Section along Row 28



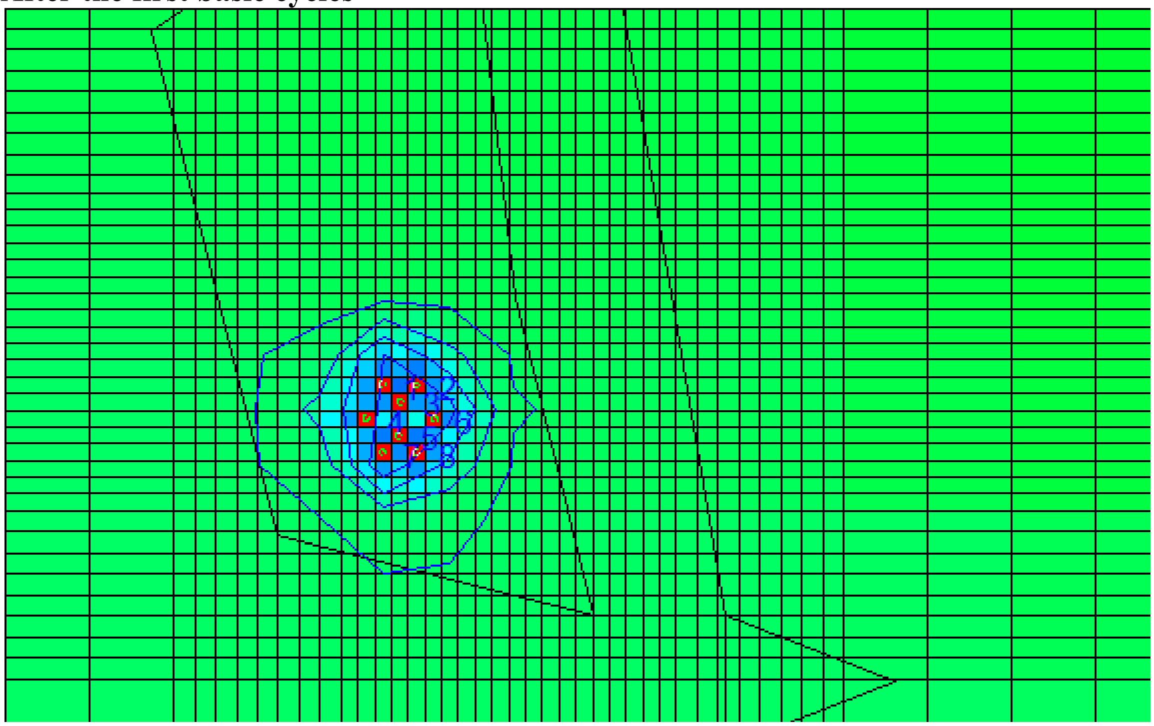
Cross-Section along Row 29



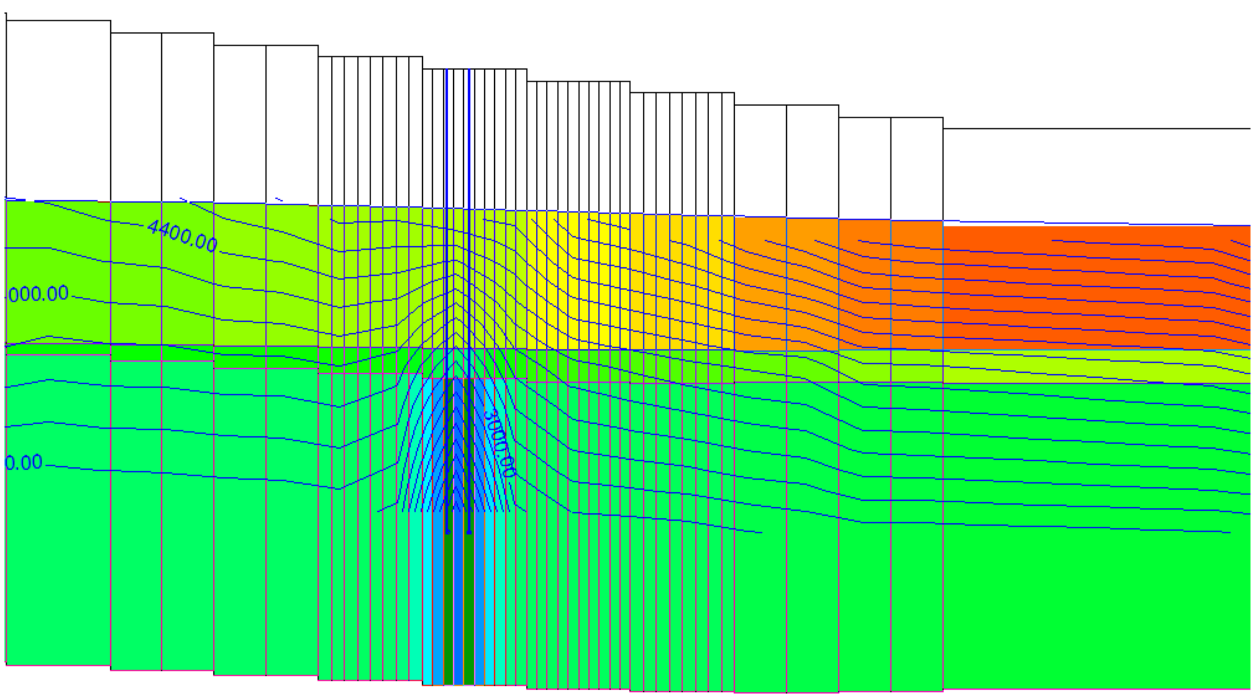
Cross-Section along Row 30



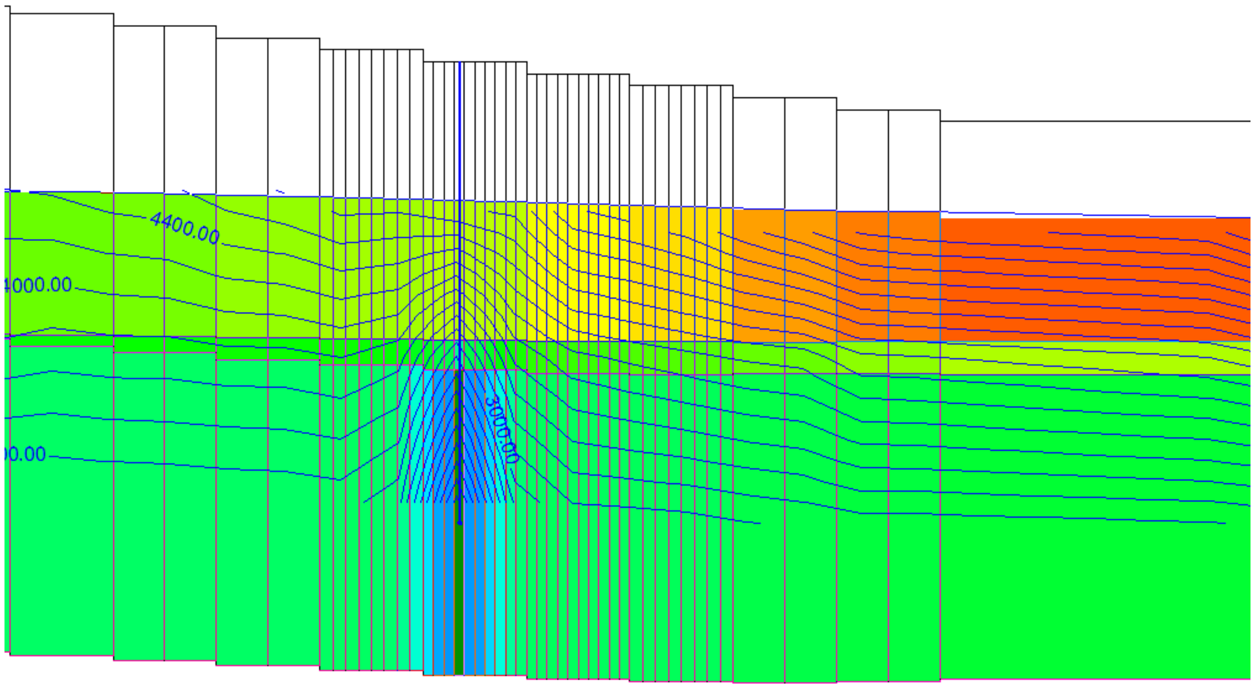
After the first basic cycles



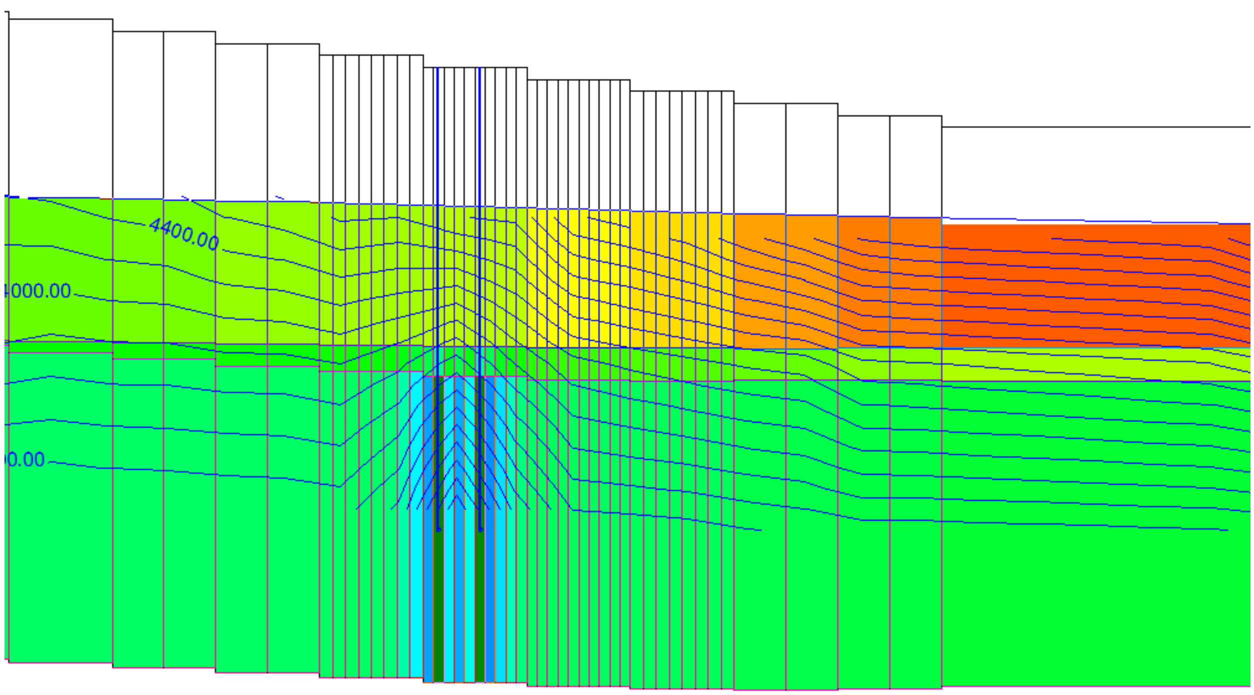
Cross-Section along Row 26



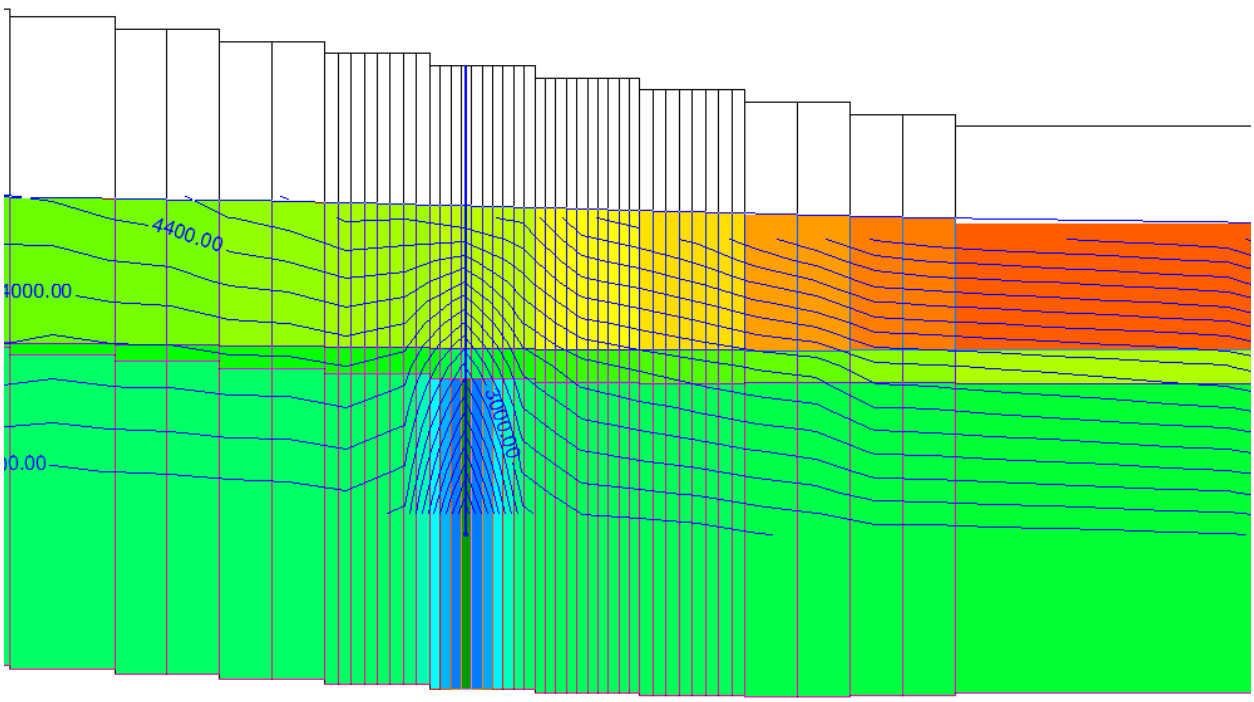
Cross-Section along Row 27



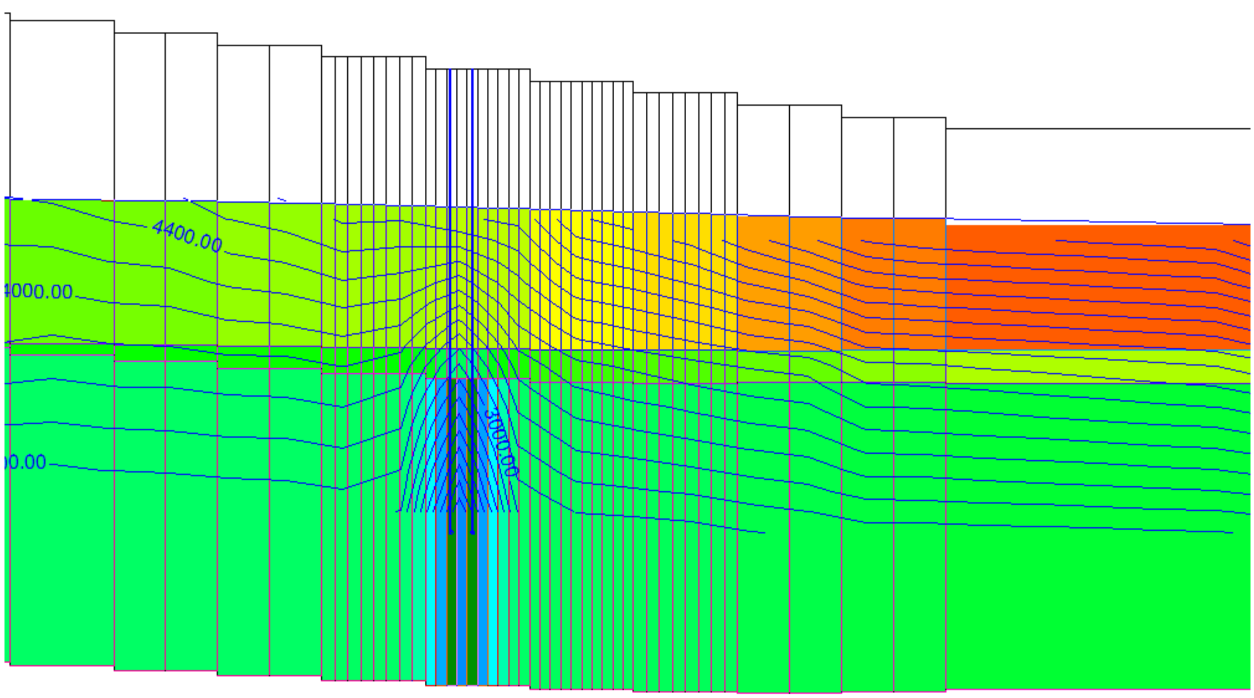
Cross-Section along Row 28



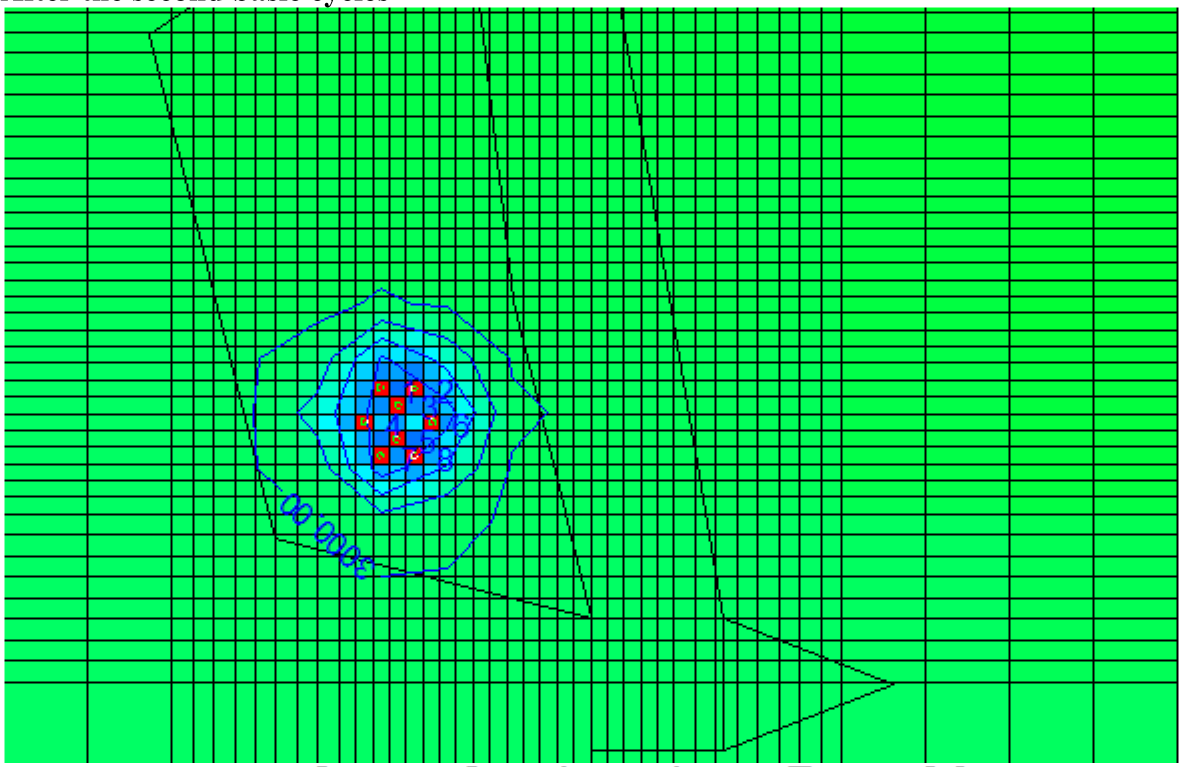
Cross-Section along Row 29



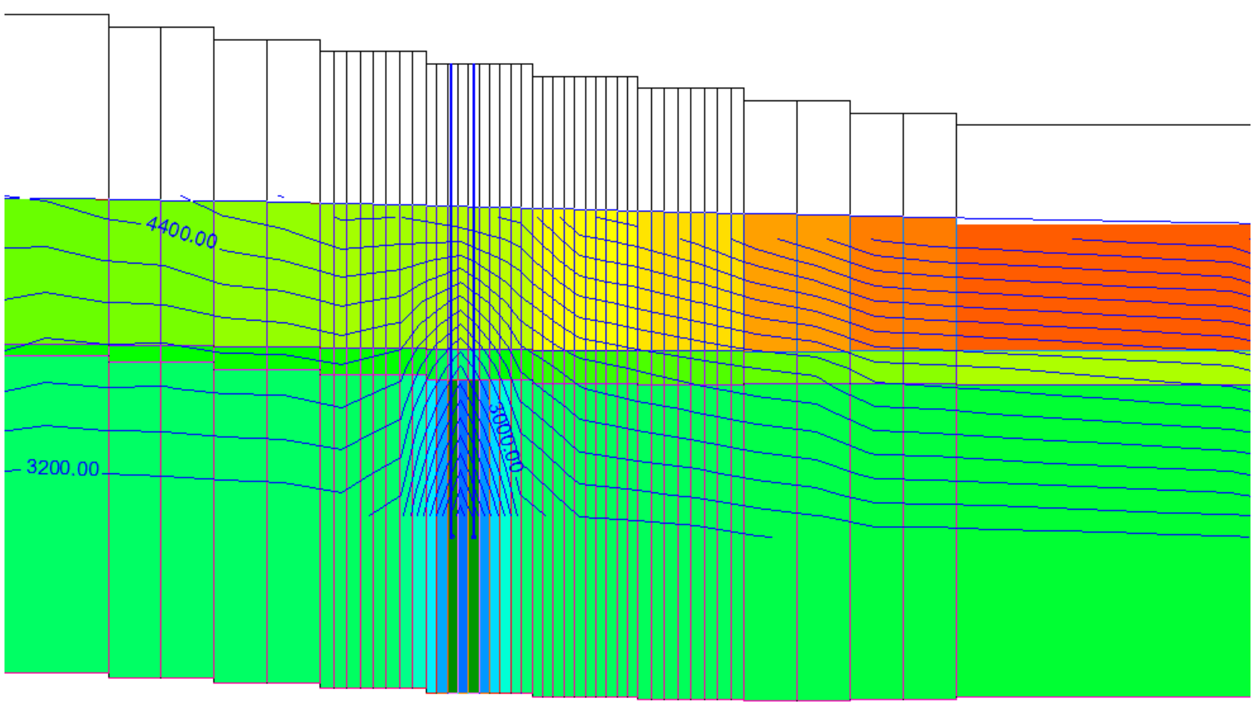
Cross-Section along Row 30



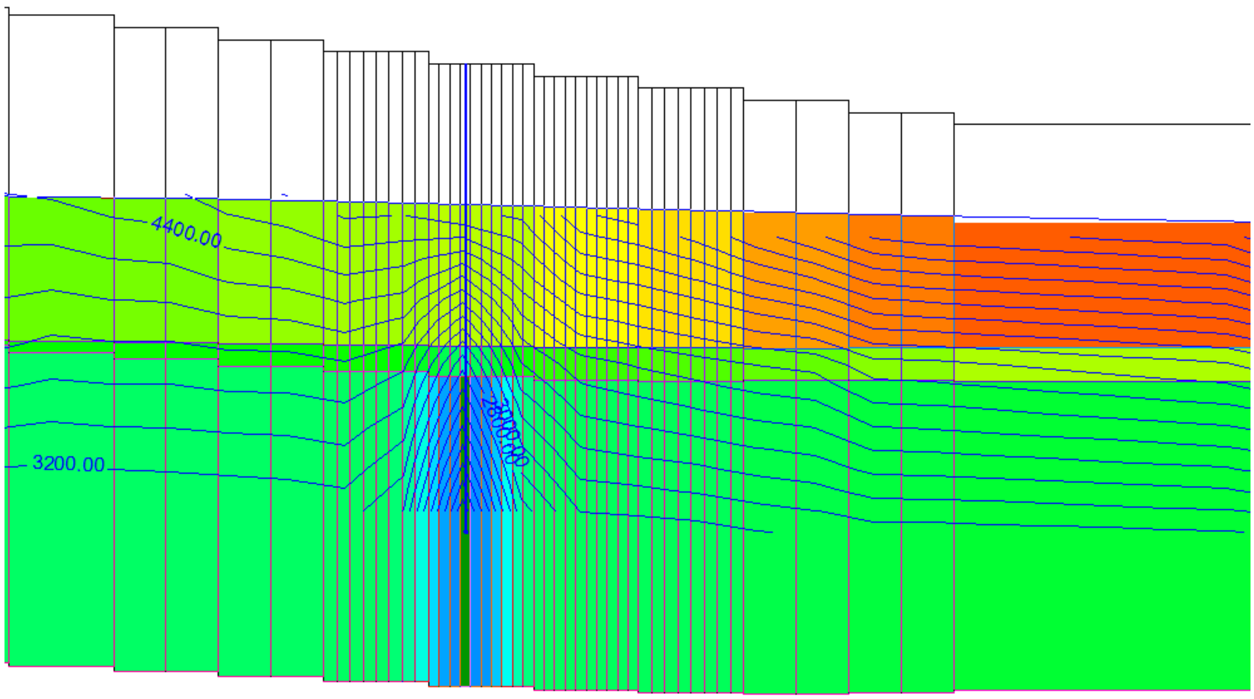
After the second basic cycles



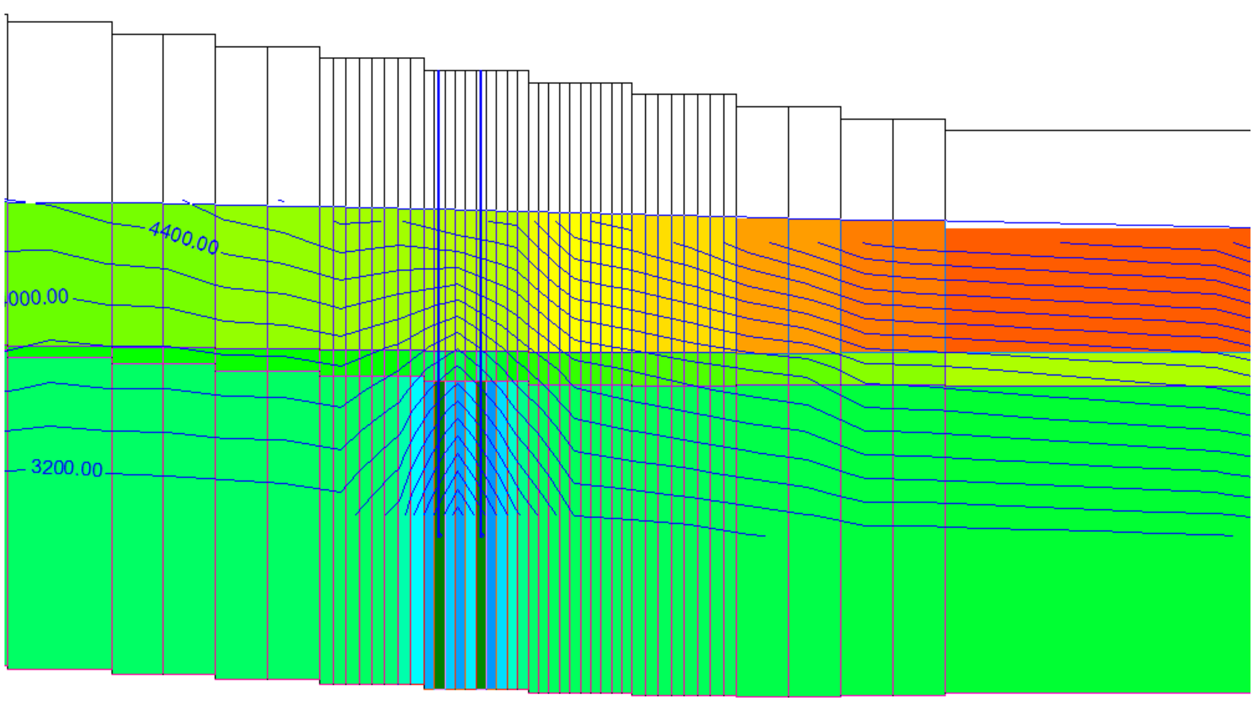
Cross-Section along Row 26



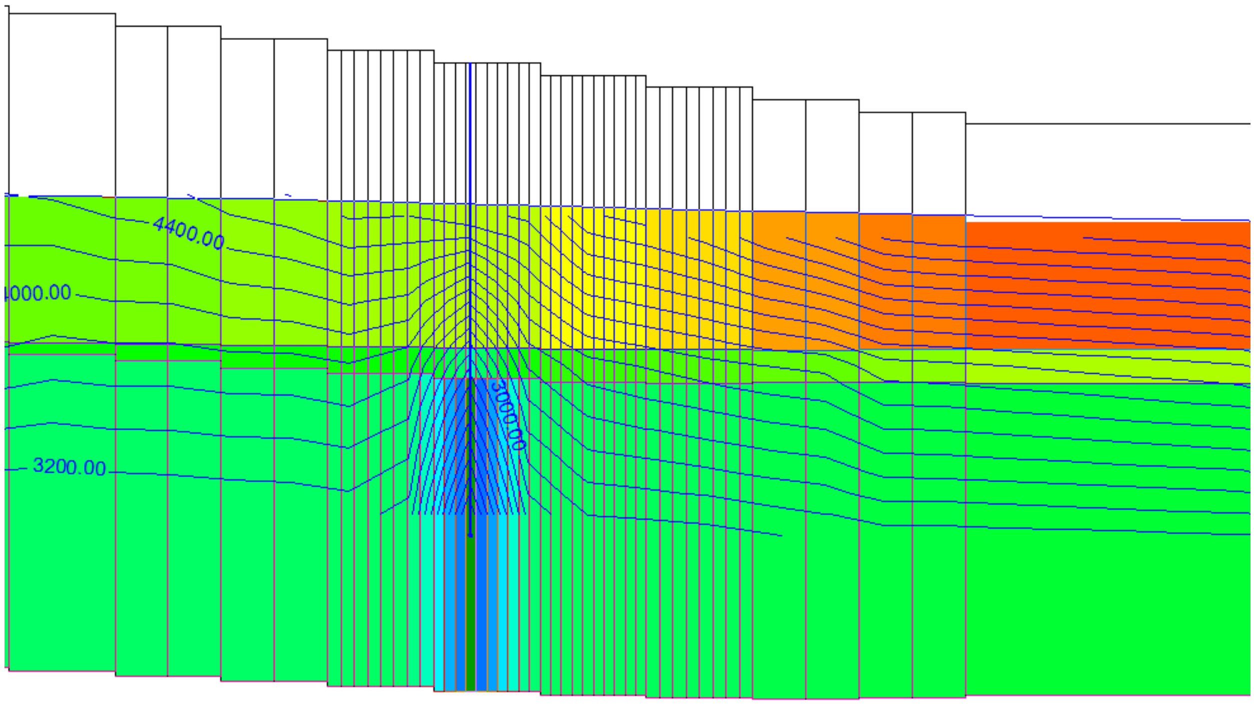
Cross-Section along Row 27



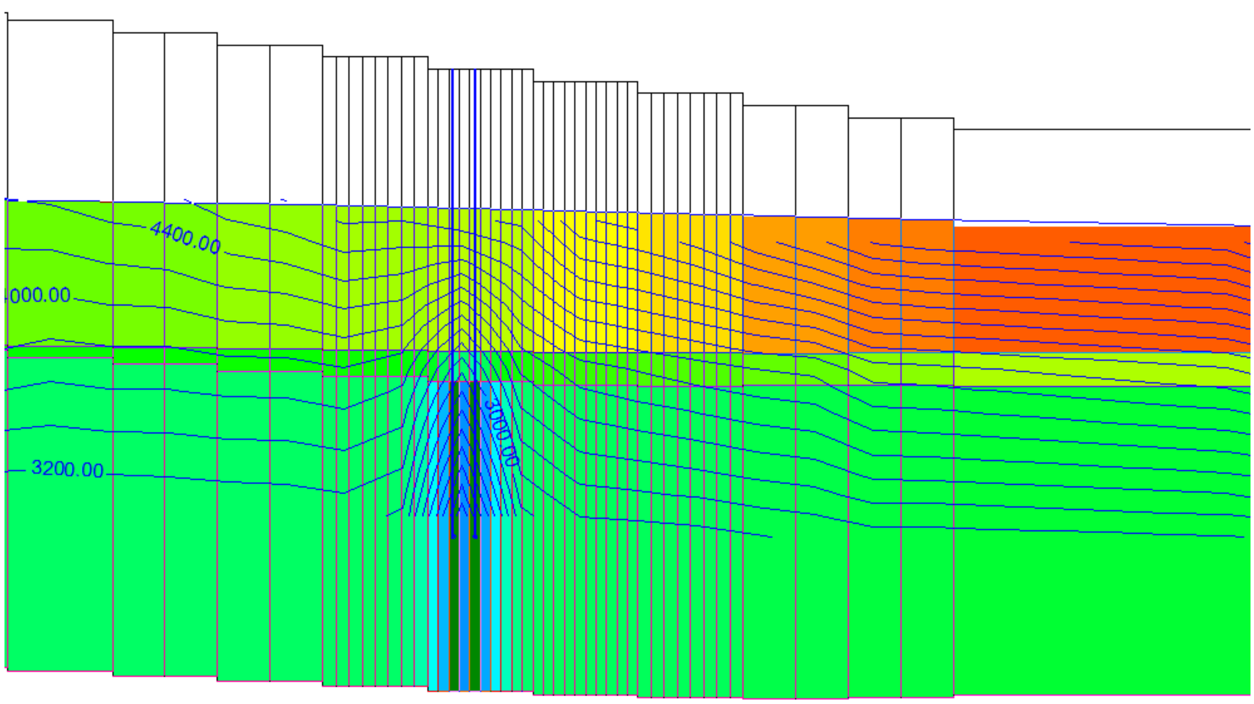
Cross-Section along Row 28



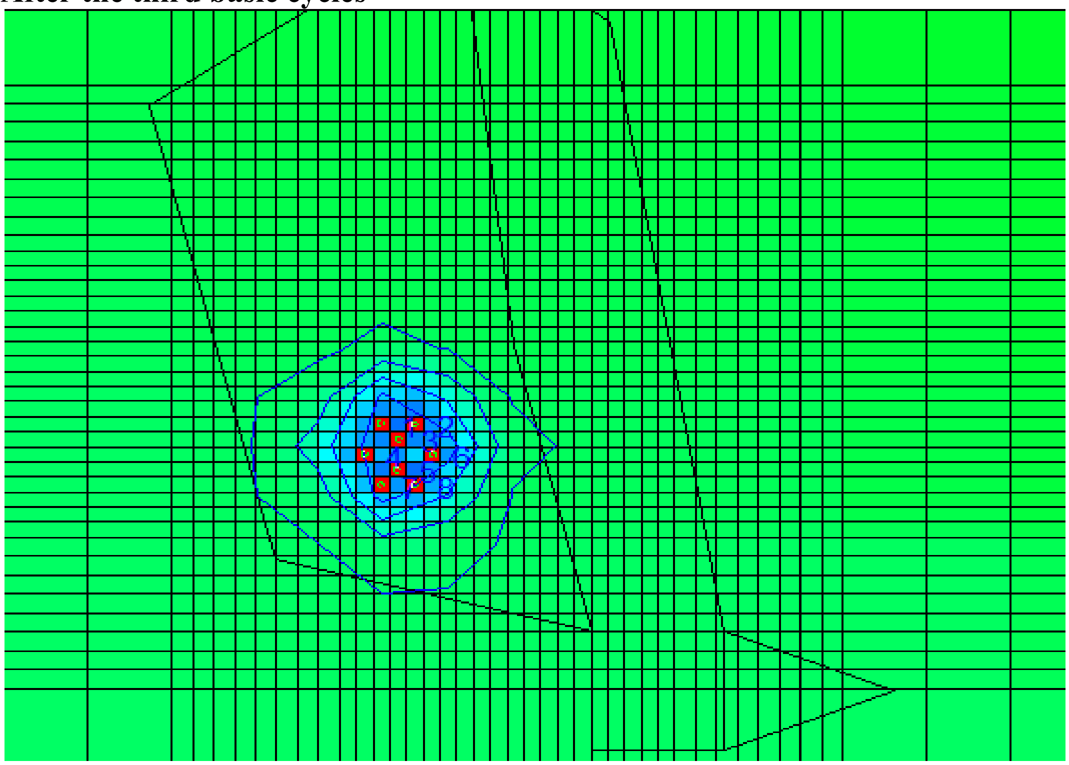
Cross-Section along Row 29



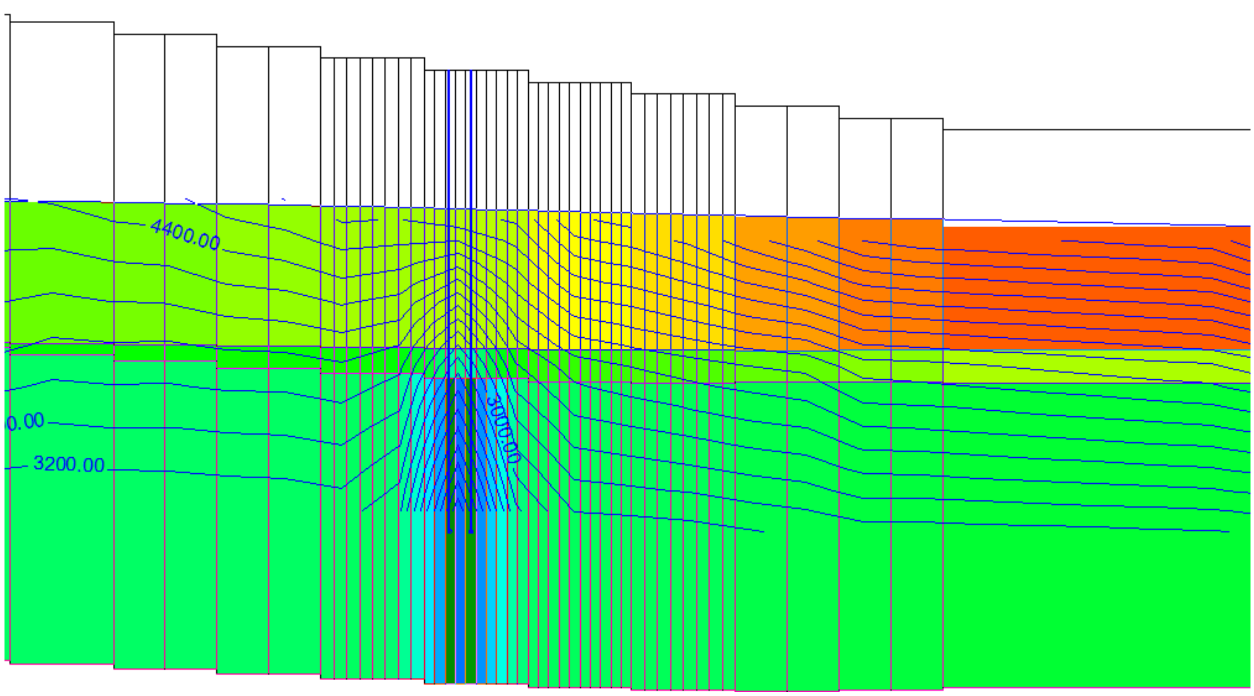
Cross-Section along Row 30



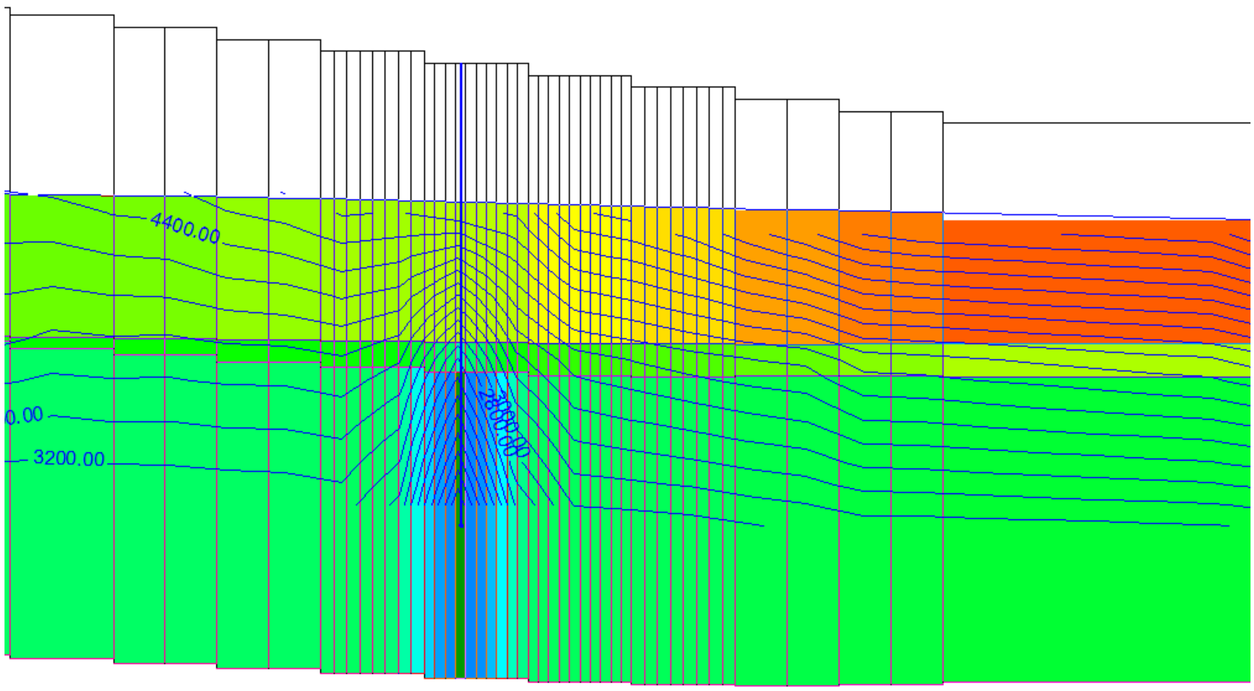
After the third basic cycles



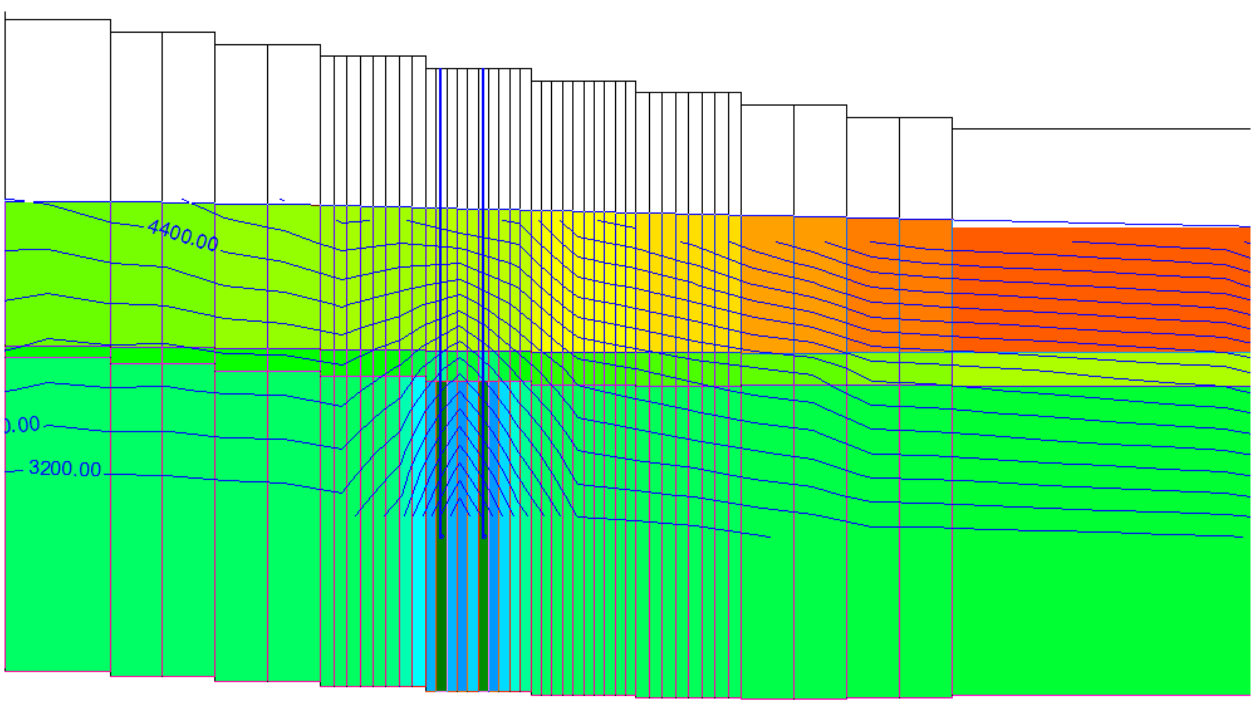
Cross-Section along Row 26



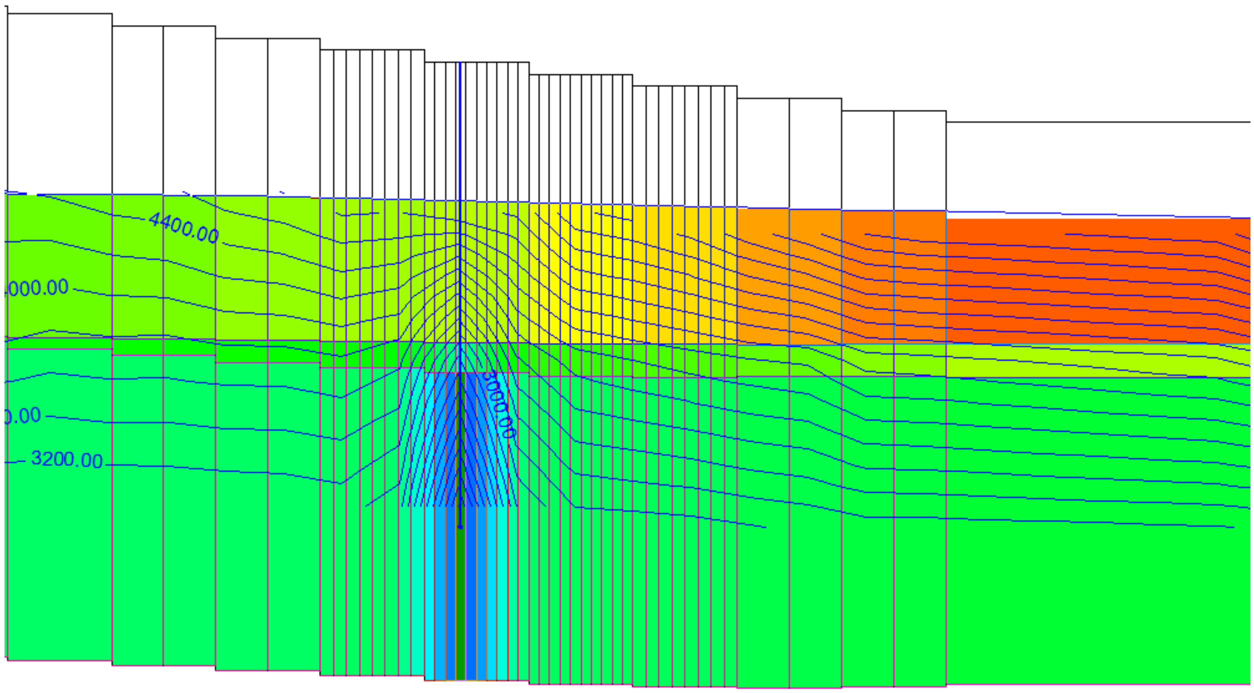
Cross-Section along Row 27



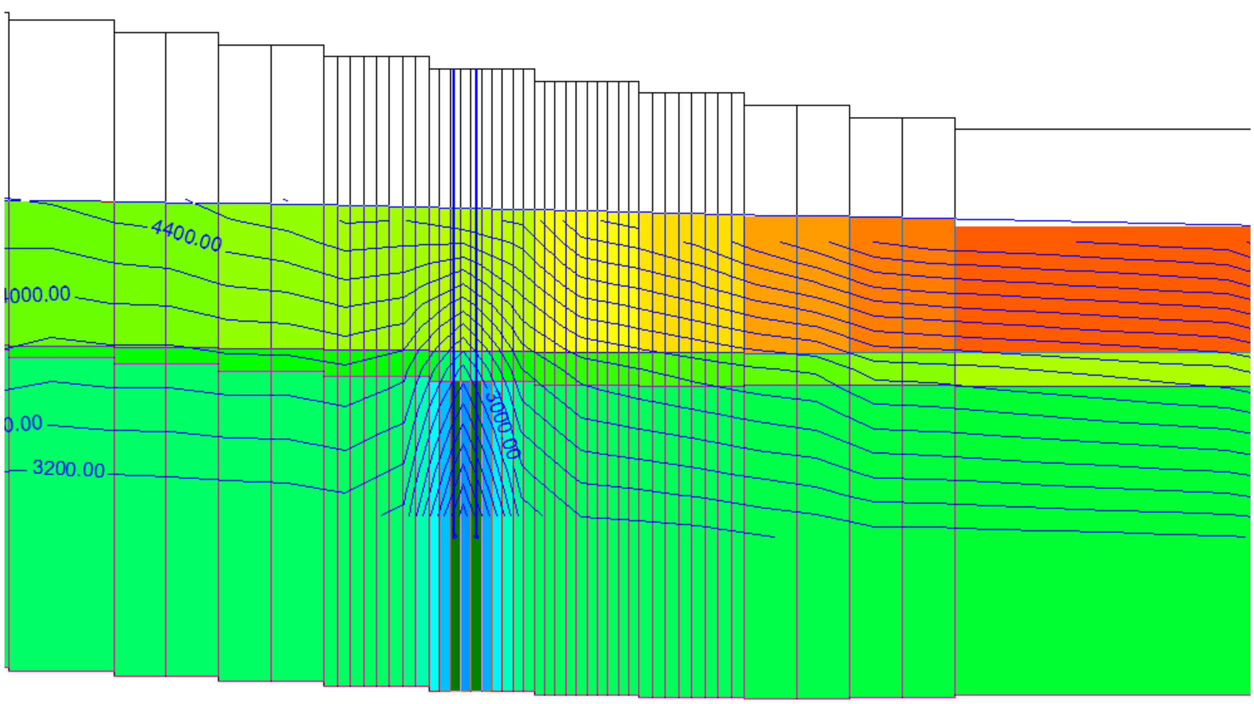
Cross-Section along Row 28

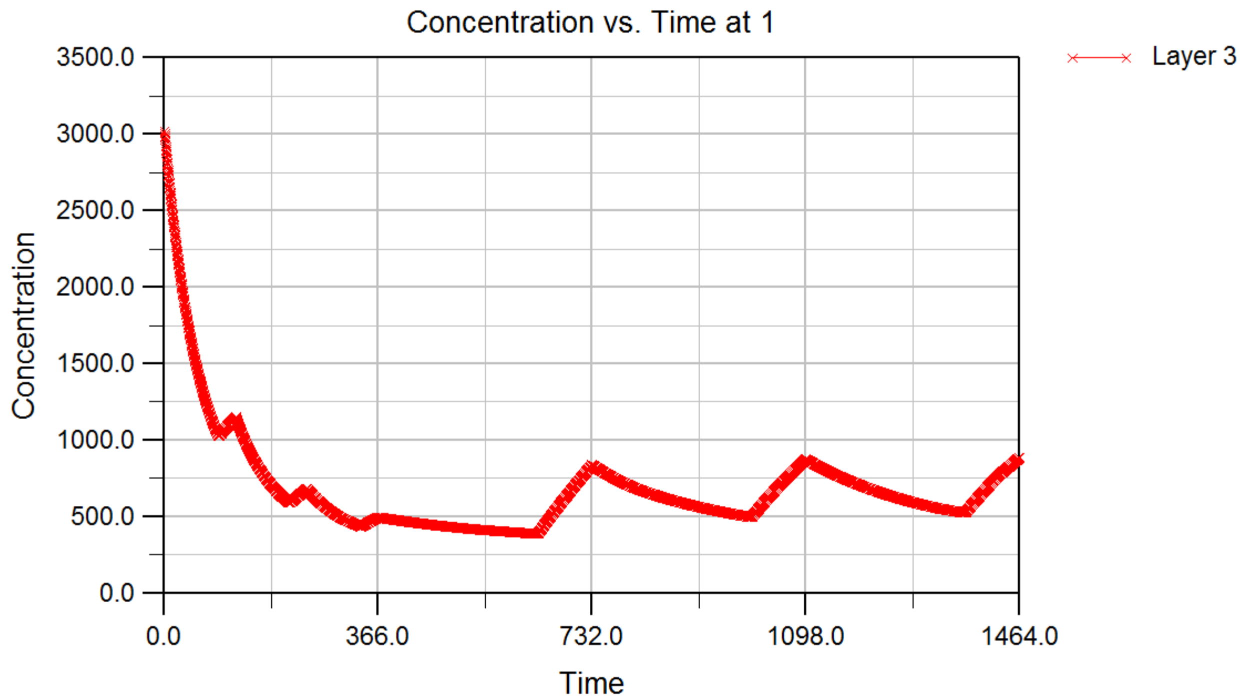


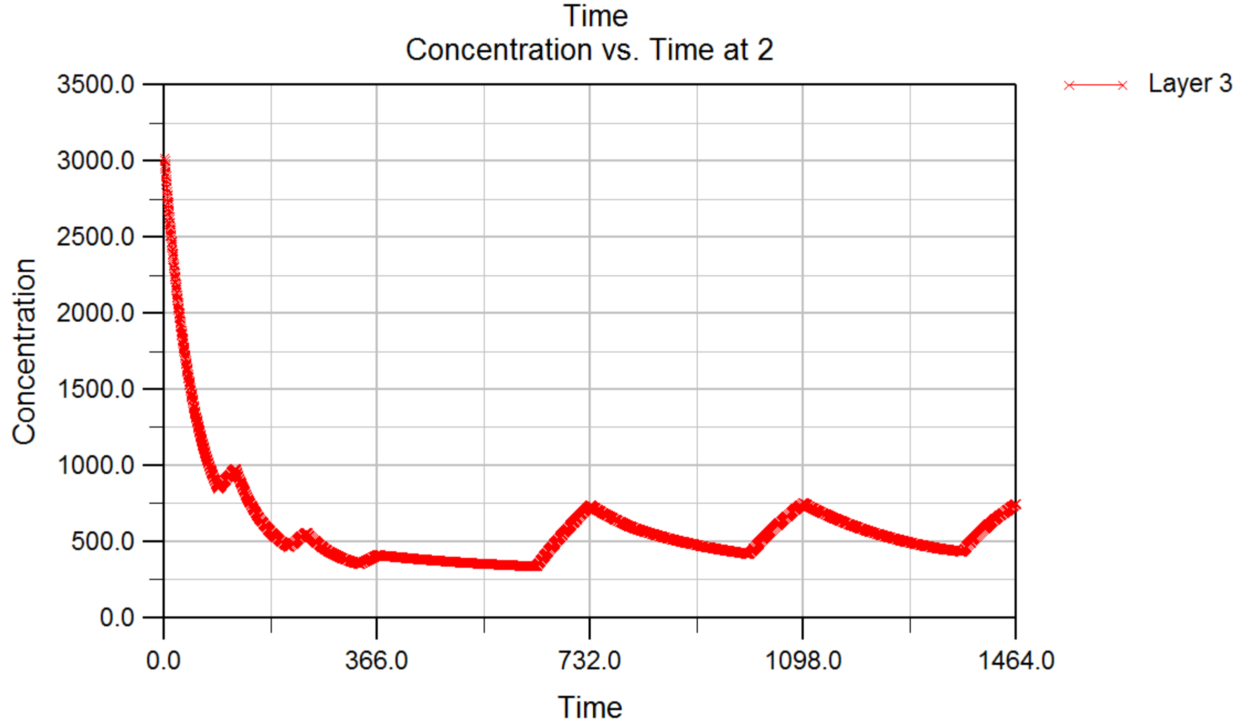
Cross-Section along Row 29

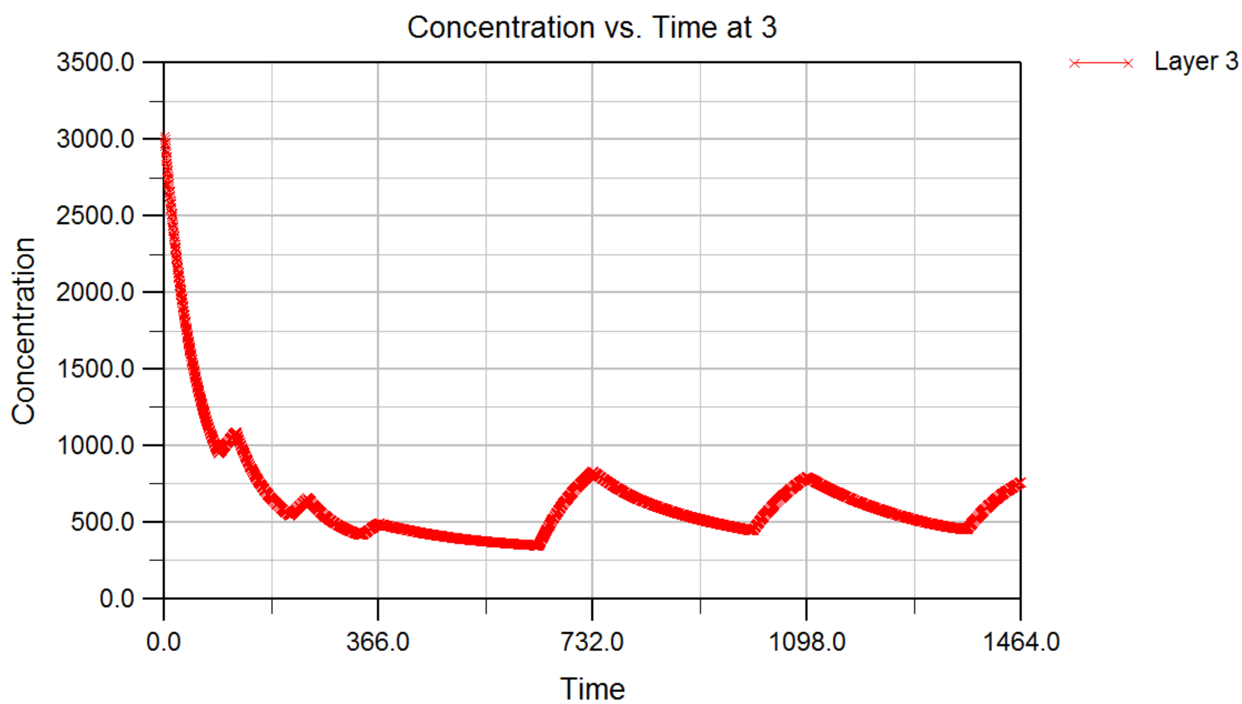


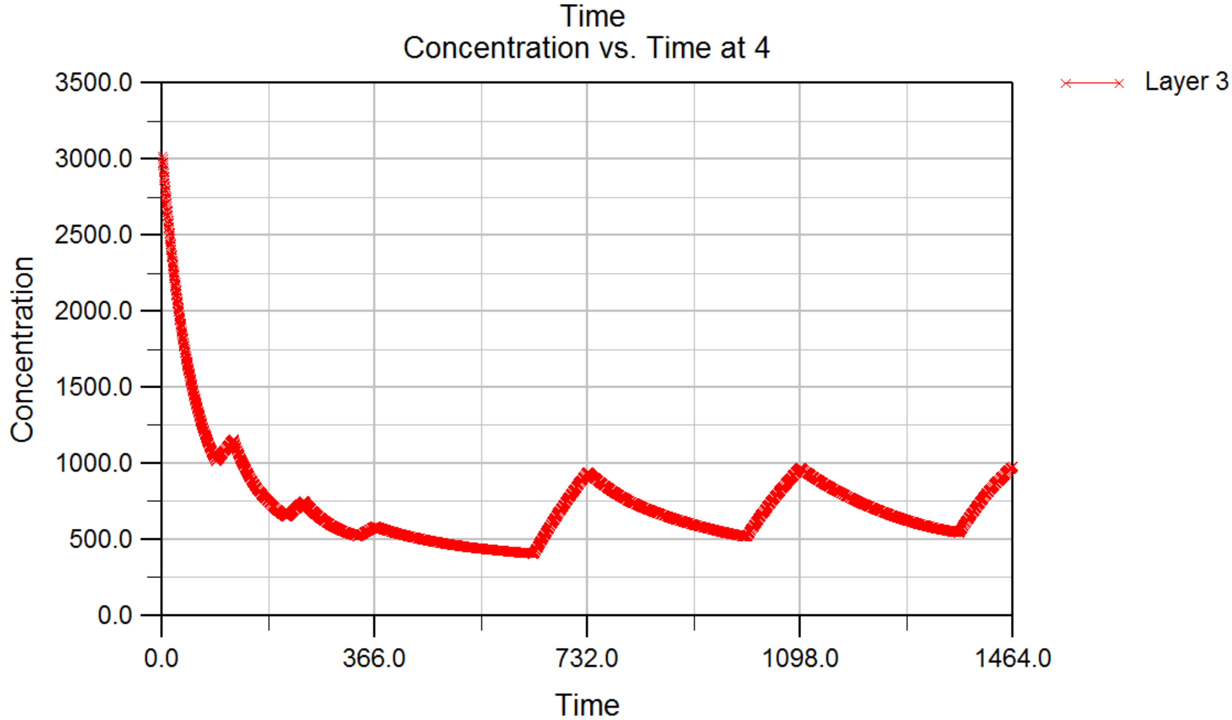
Cross-Section along Row 30

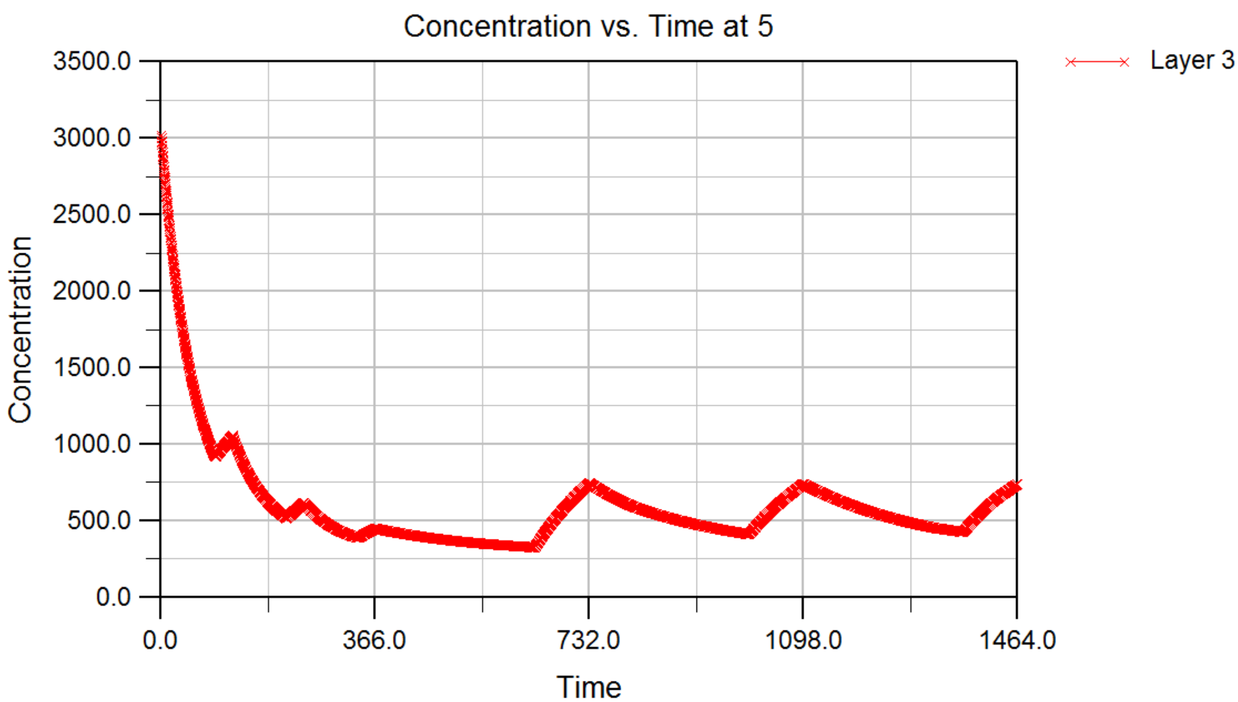


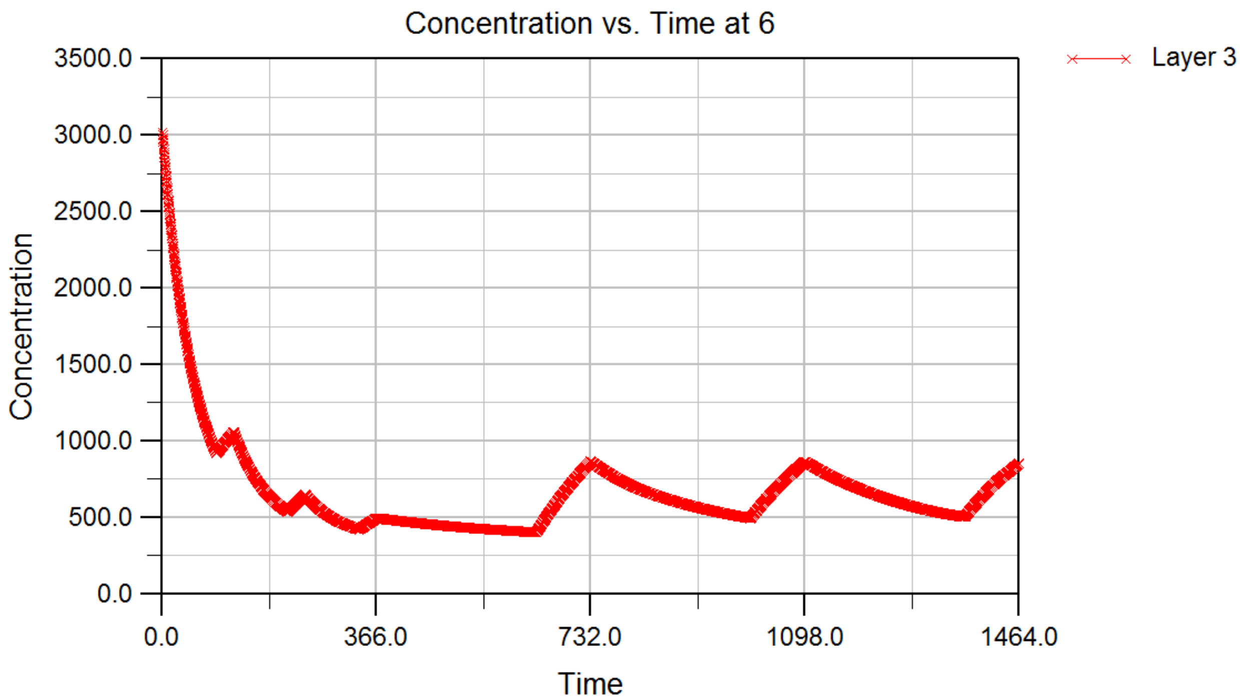

Concentration vs. Time at 1
Layer 3
Concentration
Time
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0

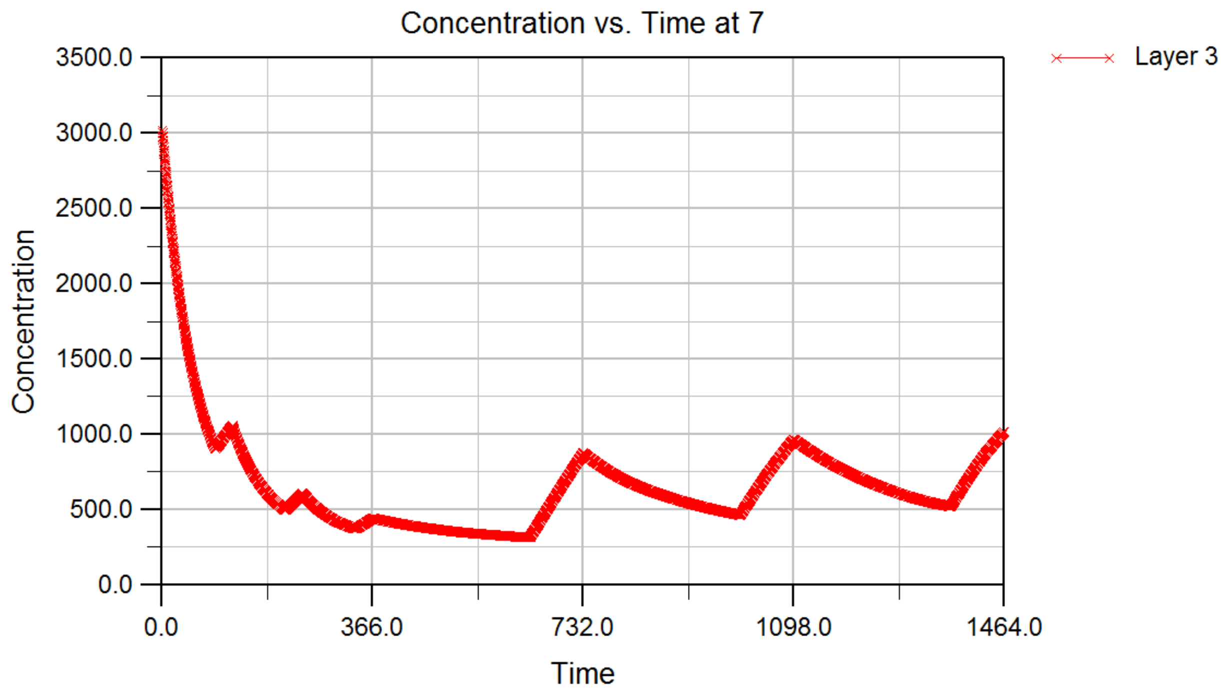

Concentration vs. Time at 2
Layer 3
Concentration
Time
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0


Concentration vs. Time at 3
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time

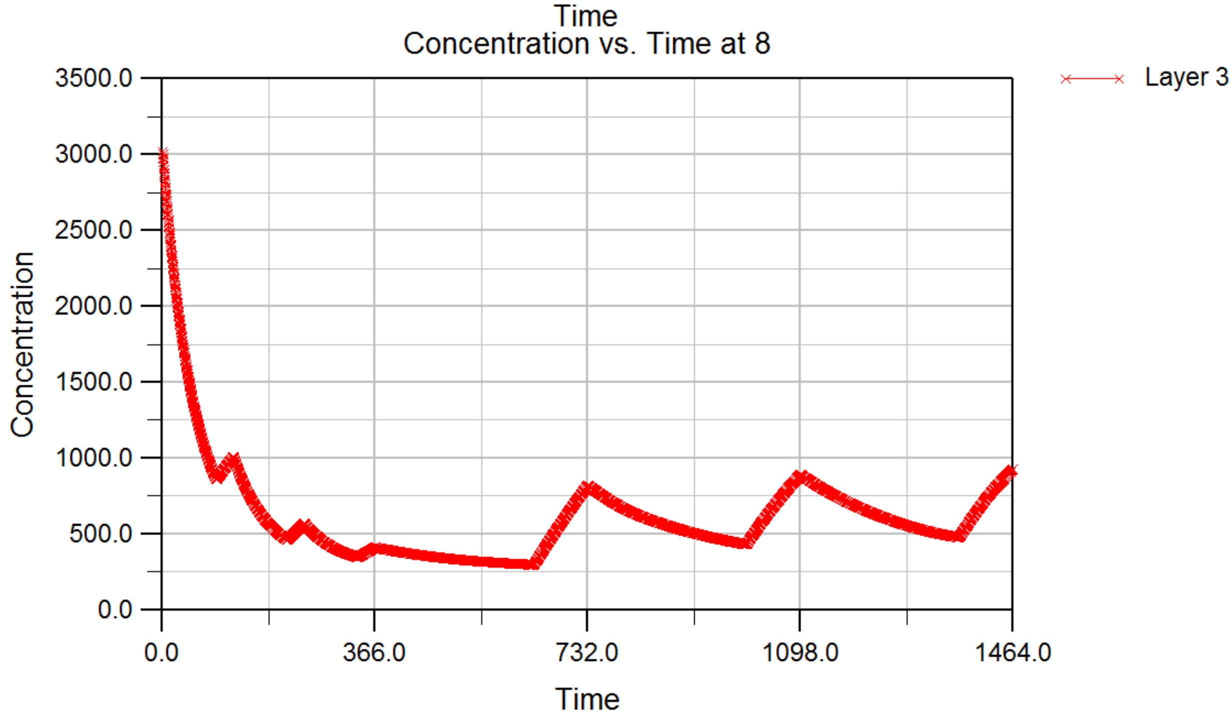

Concentration vs. Time at 4
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time


Concentration vs. Time at 5
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time


Concentration vs. Time at 6
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time

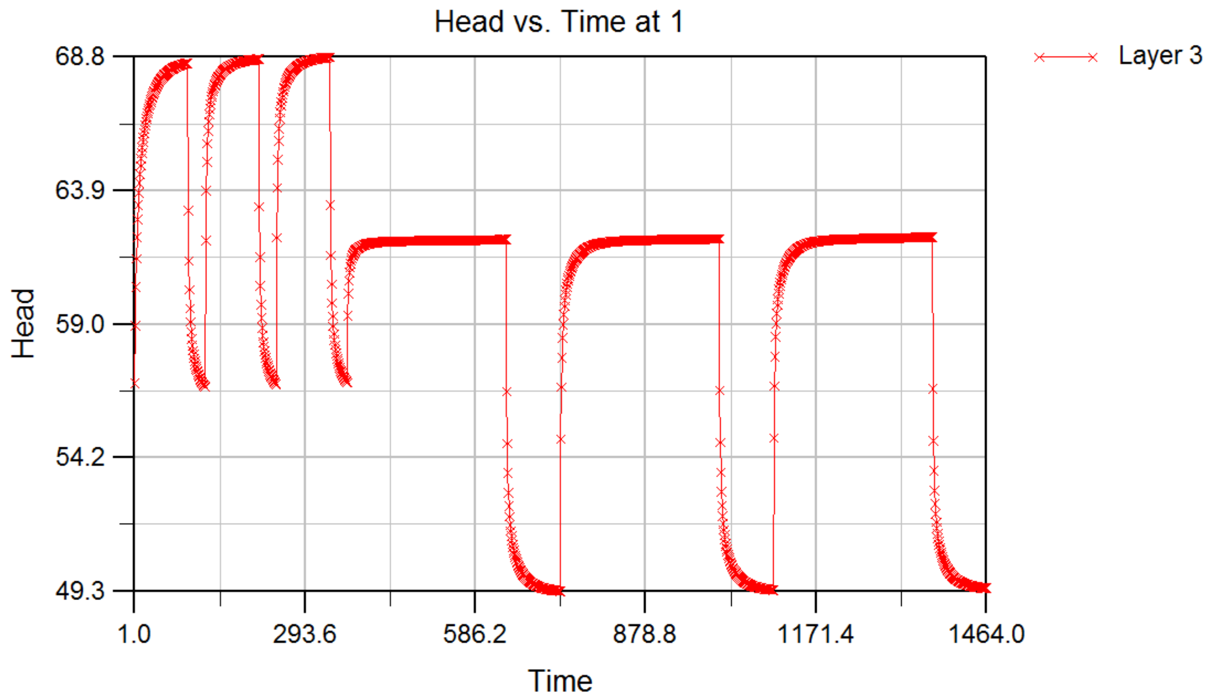


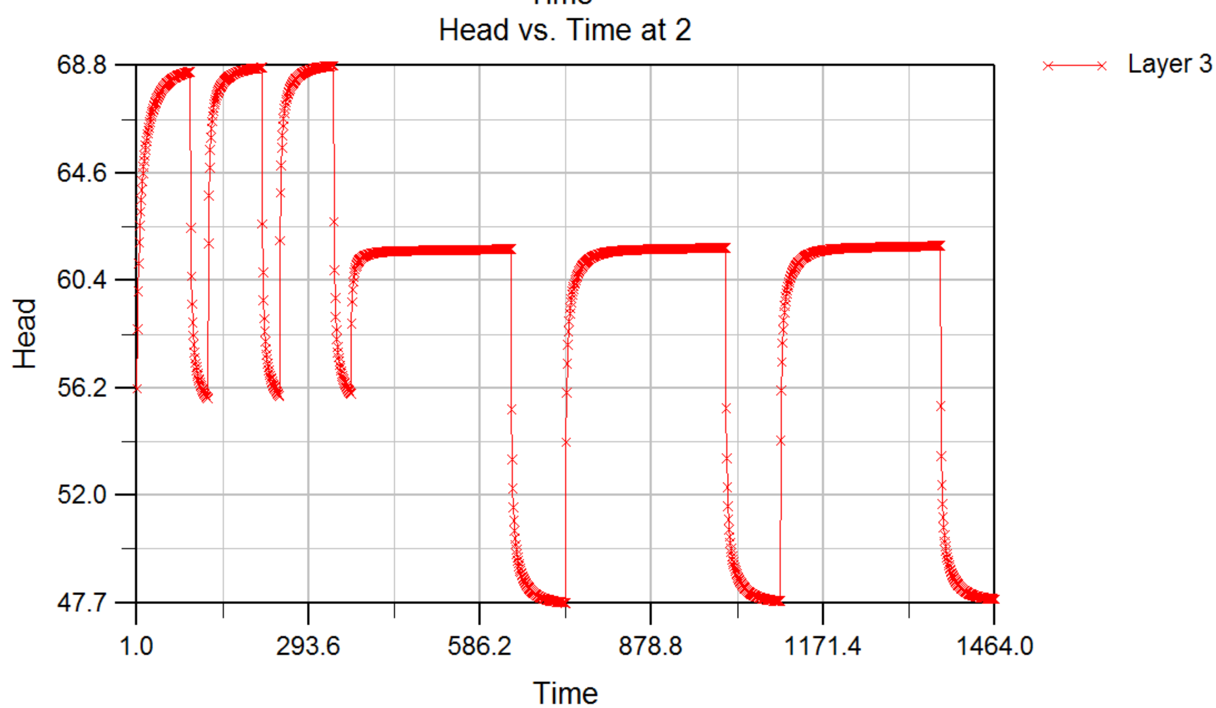
Concentration vs. Time at 7
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time

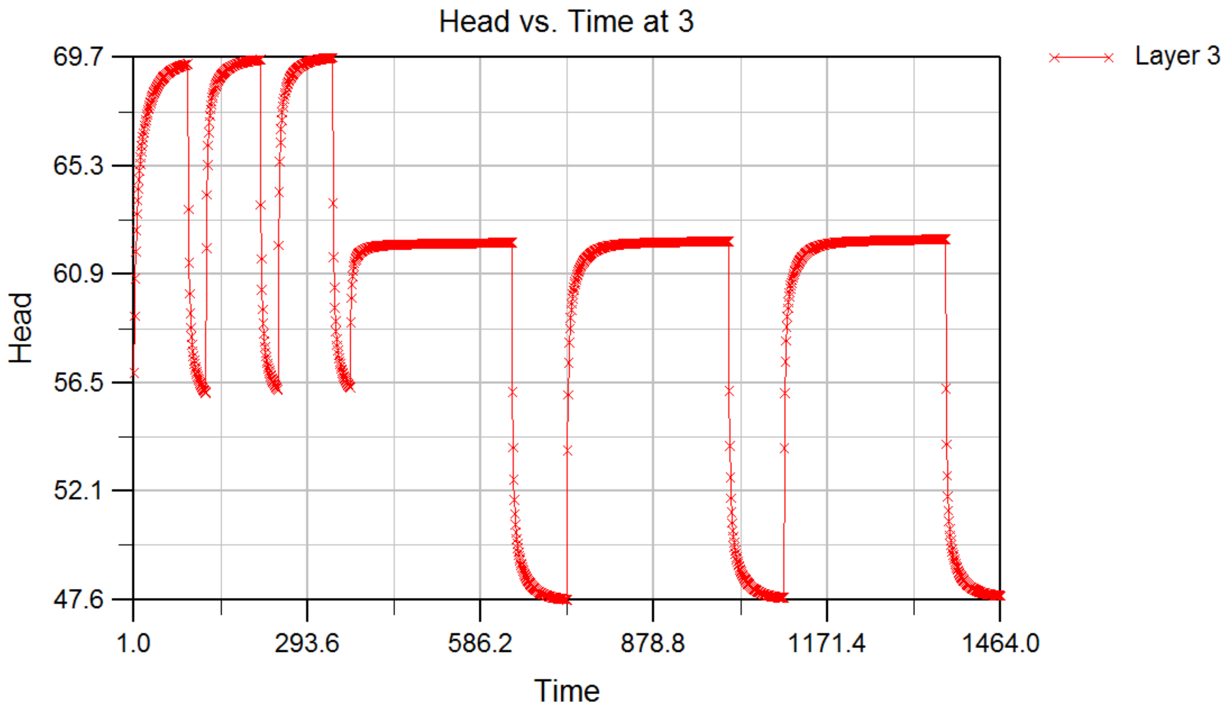


Concentration vs. Time at 8
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time

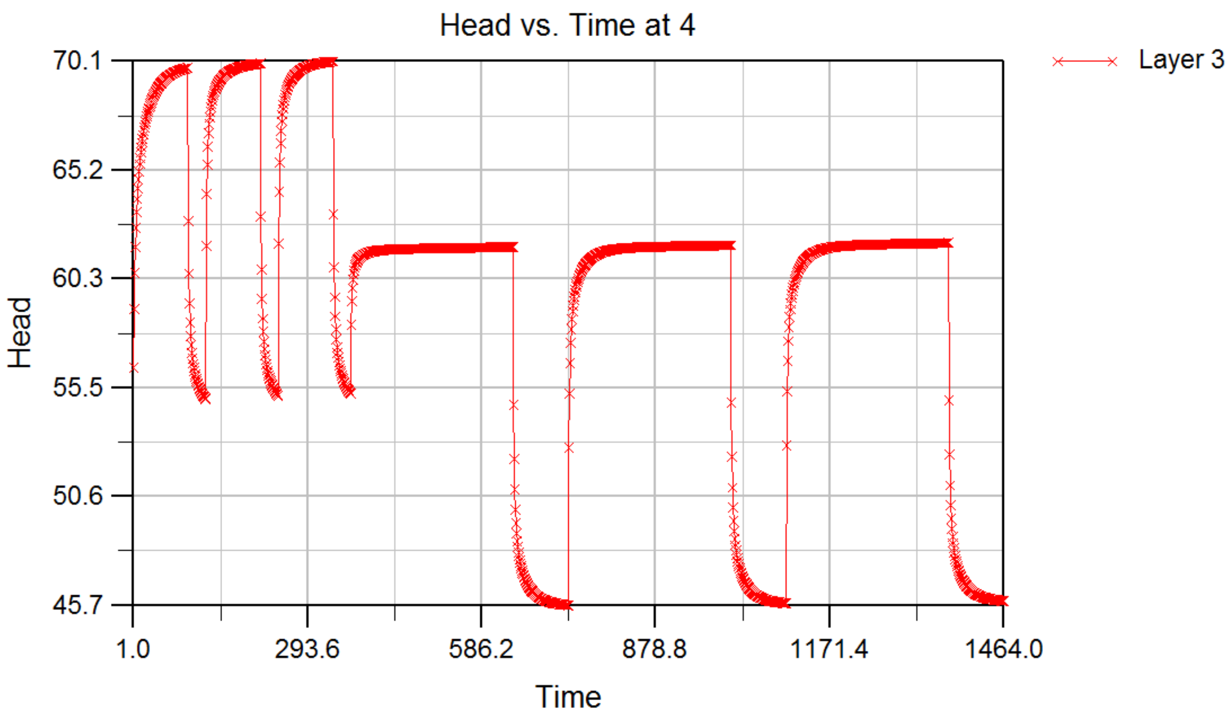
RUN 5 (MODFLOW & MT3D)



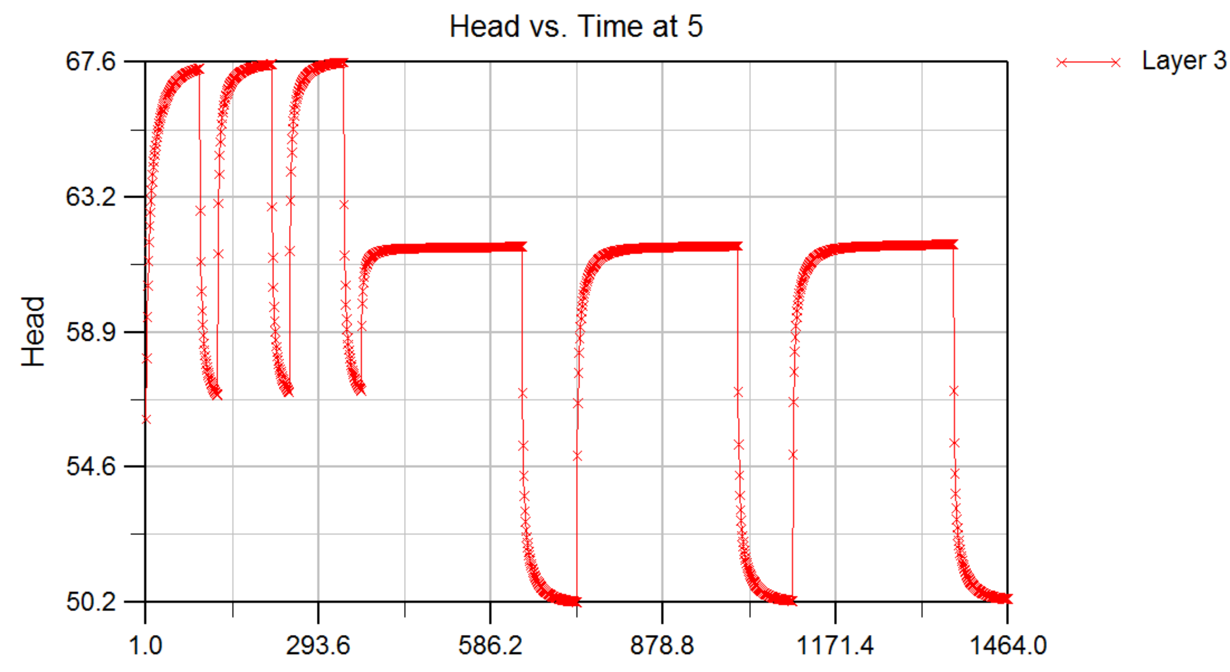


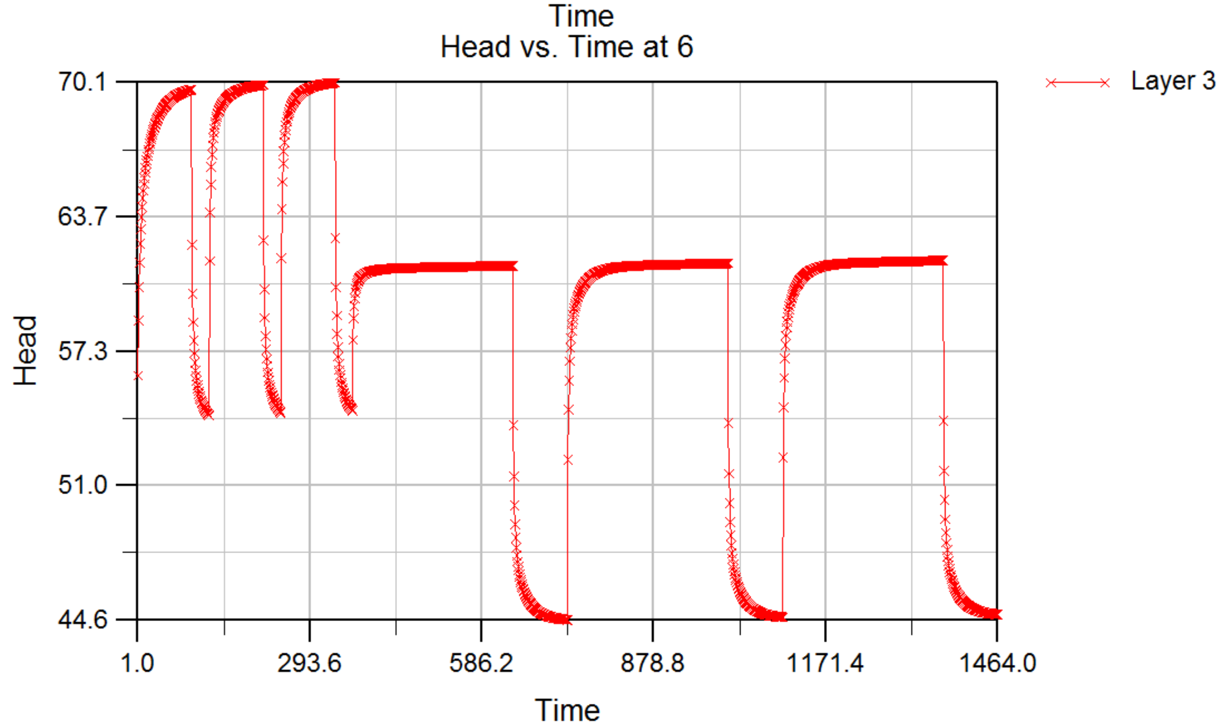


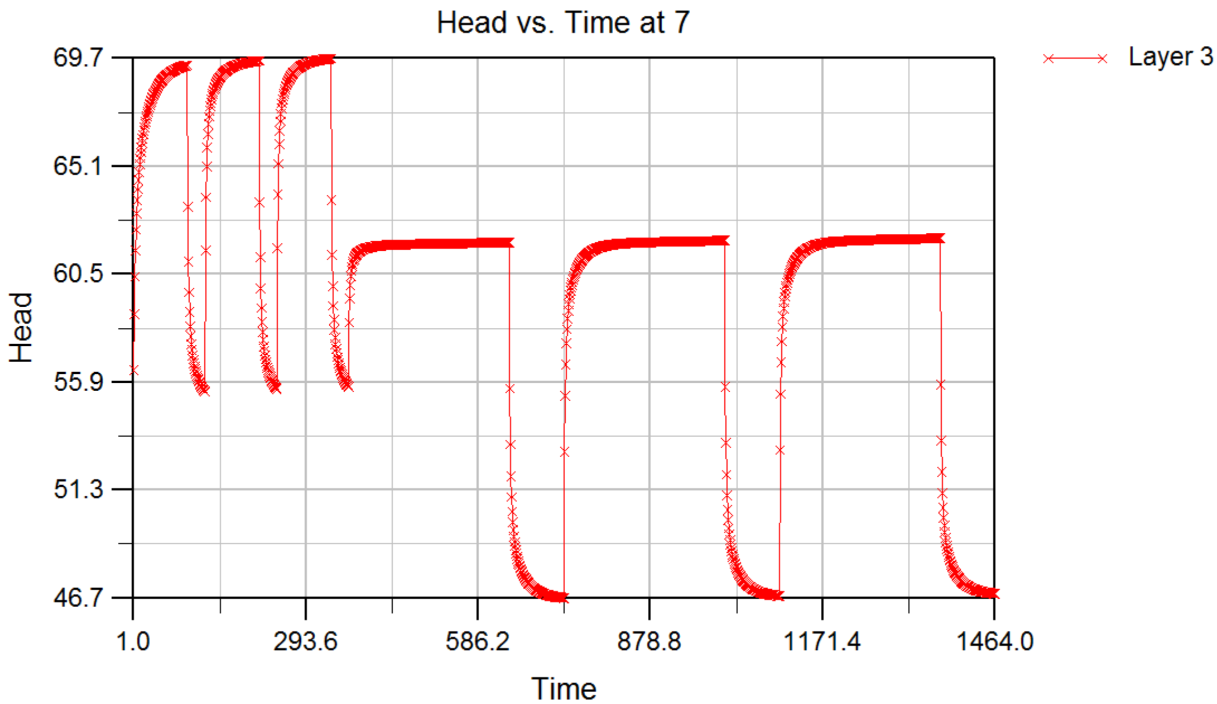
Head vs. Time at 3
Layer 3
69.7
65.3
60.9
56.5
52.1
47.6
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

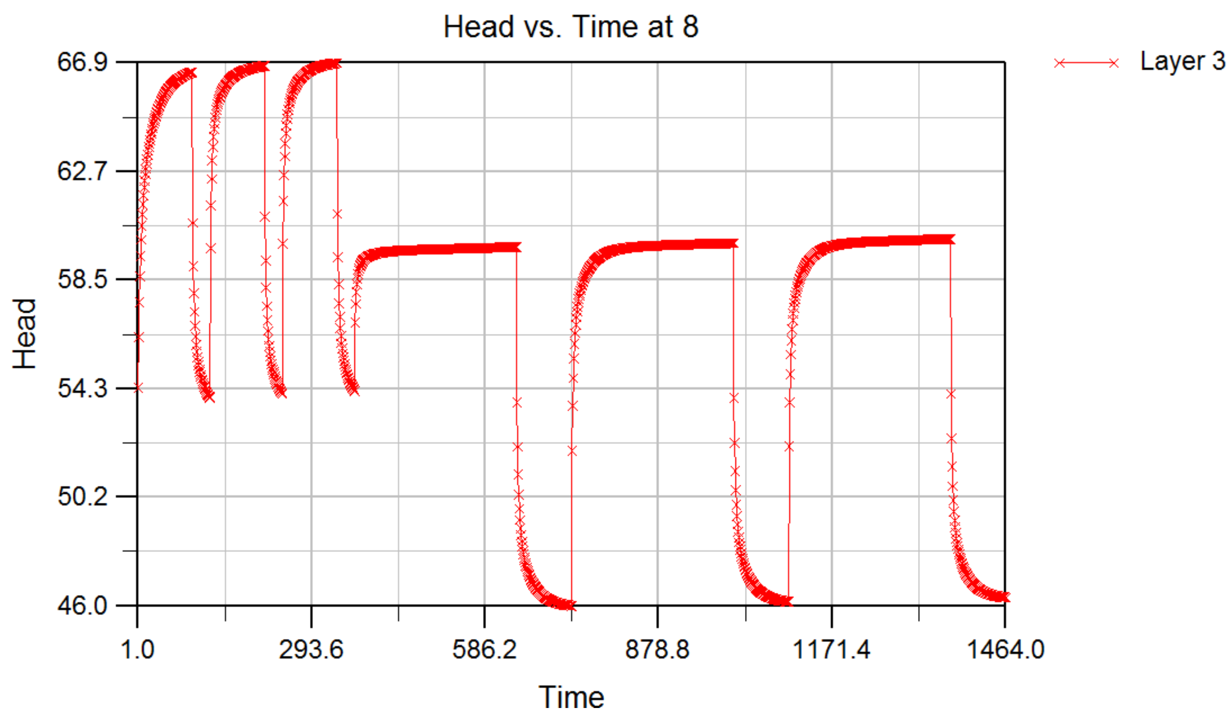


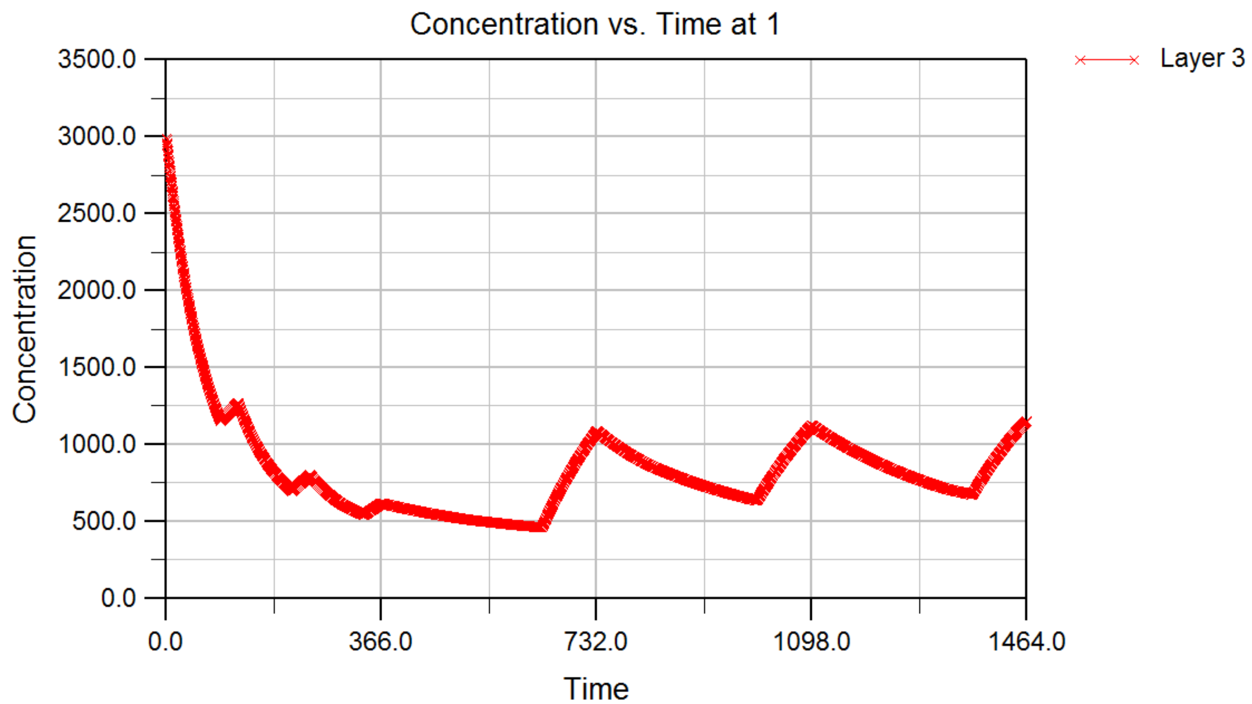
Head vs. Time at 4
Layer 3
70.1
65.2
60.3
55.5
50.6
45.7
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

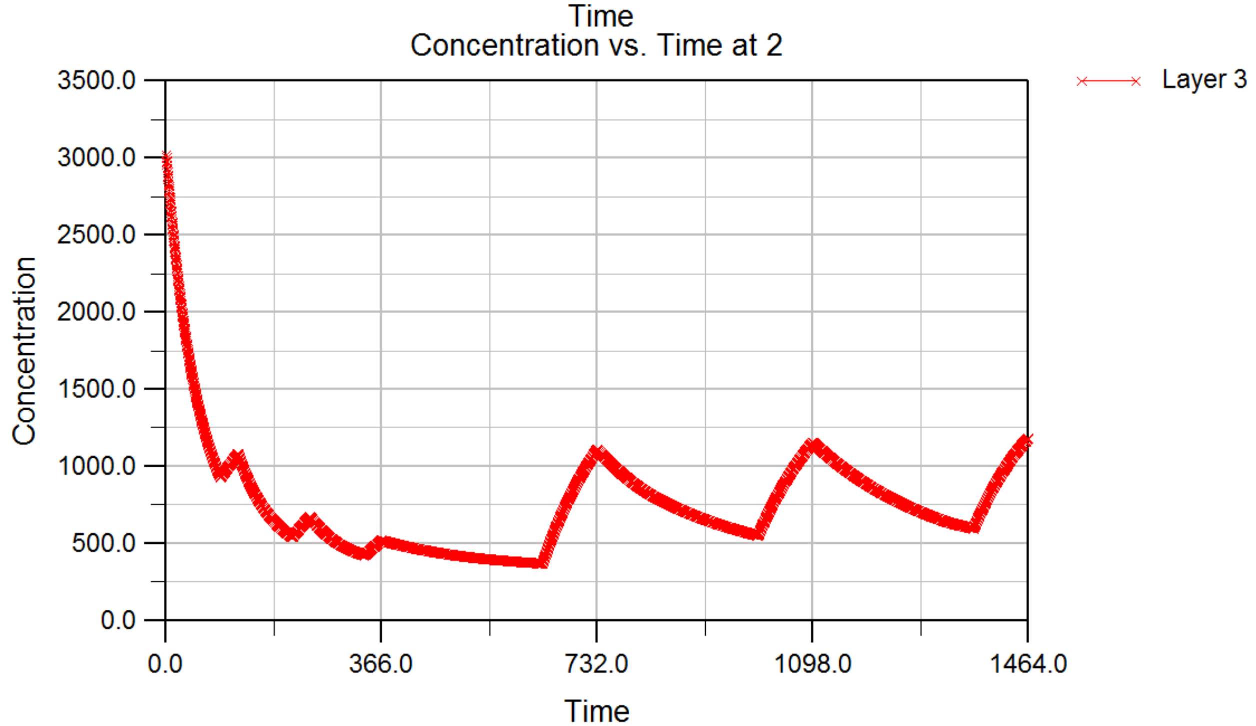

Head vs. Time at 5
Layer 3
67.6
63.2
58.9
54.6
50.2
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

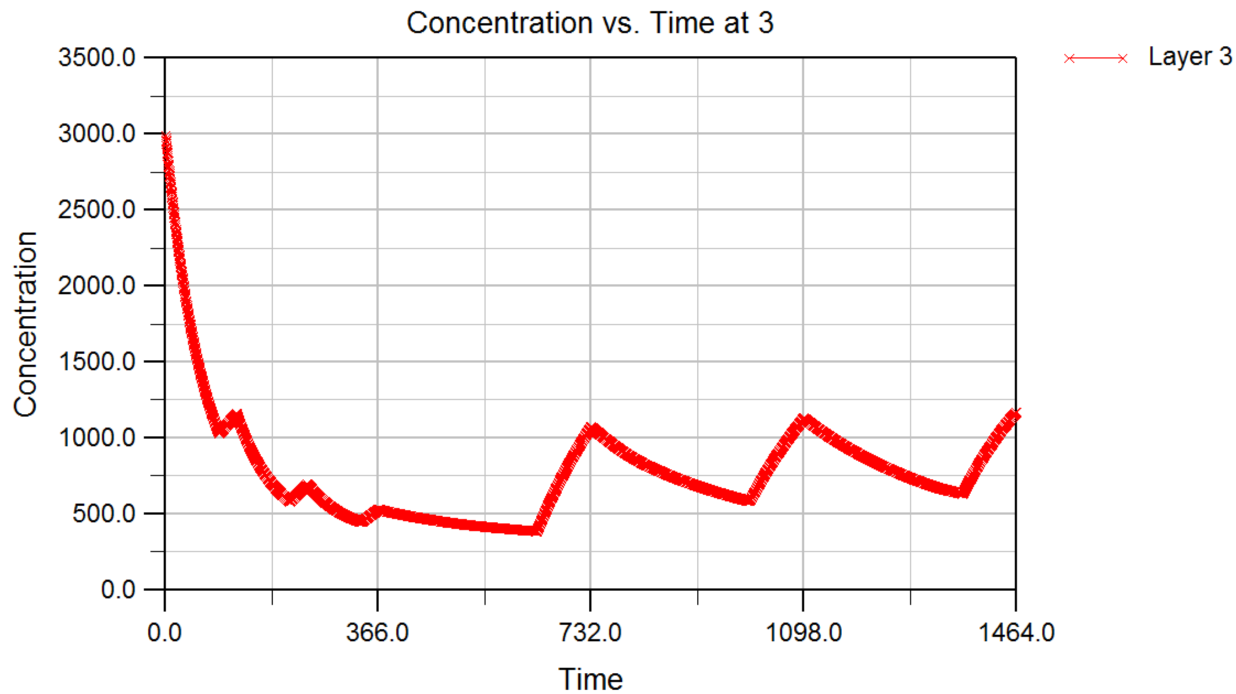

Head vs. Time at 6
Layer 3
70.1
63.7
57.3
51.0
44.6
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time


Head vs. Time at 7
Layer 3
69.7
65.1
60.5
55.9
51.3
46.7
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

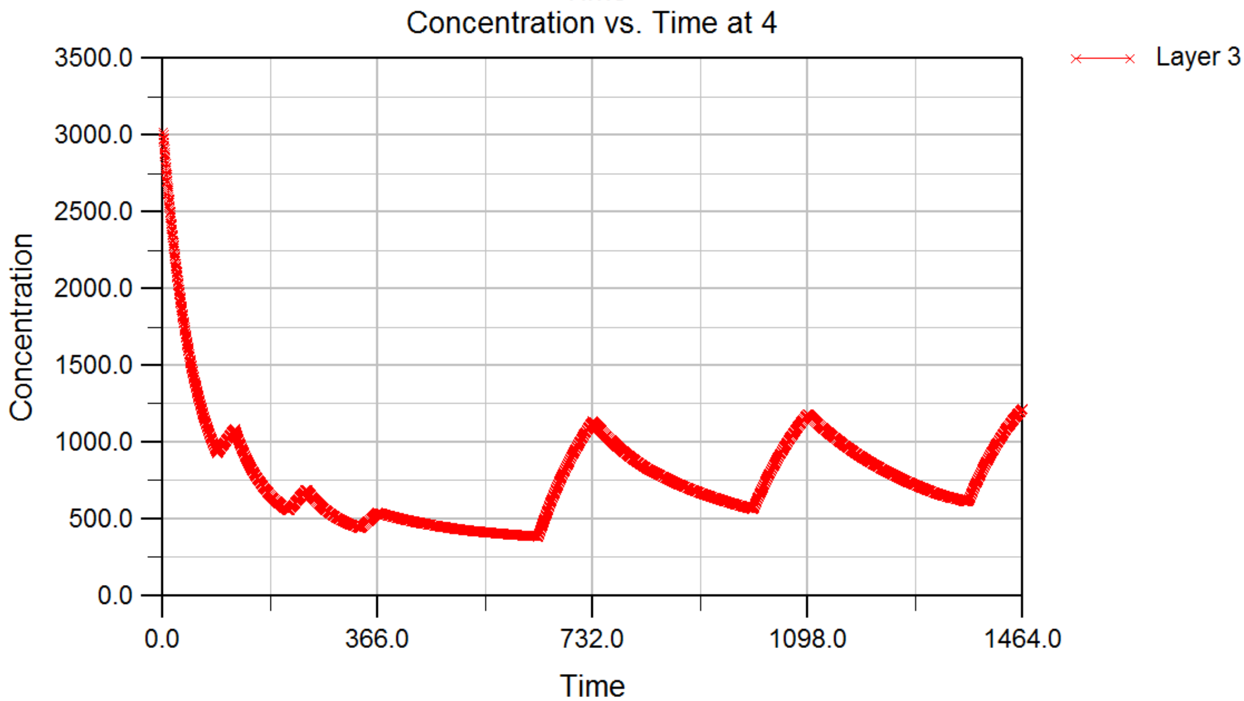

Head vs. Time at 8
Layer 3
66.9
62.7
58.5
54.3
50.2
46.0
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time


Concentration vs. Time at 1
Layer 3
Concentration
Time
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0

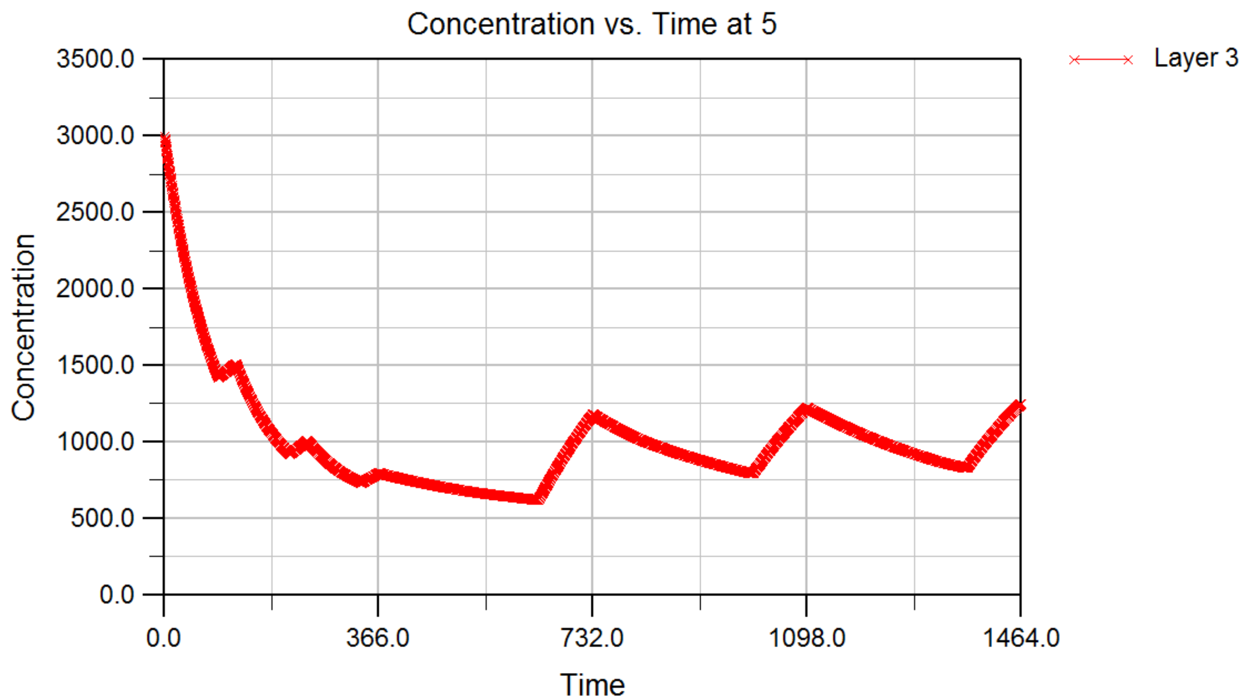

Concentration vs. Time at 2
Layer 3
Concentration
Time
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0

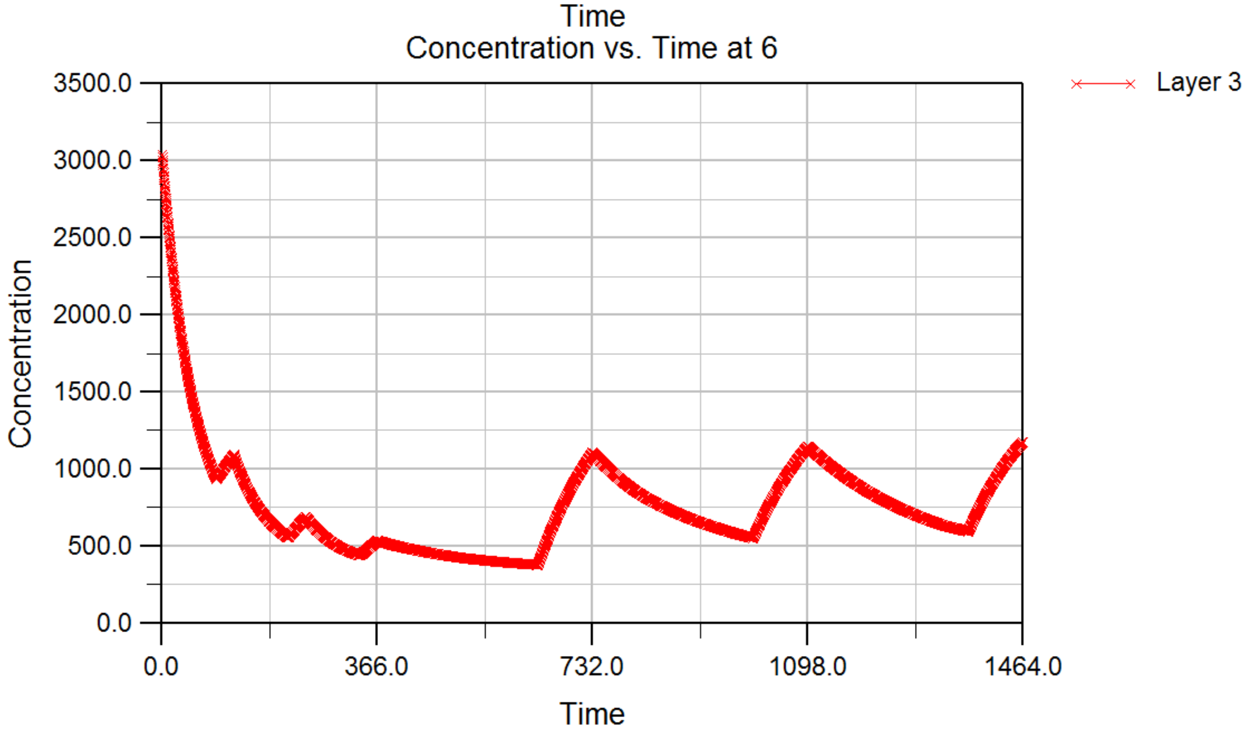


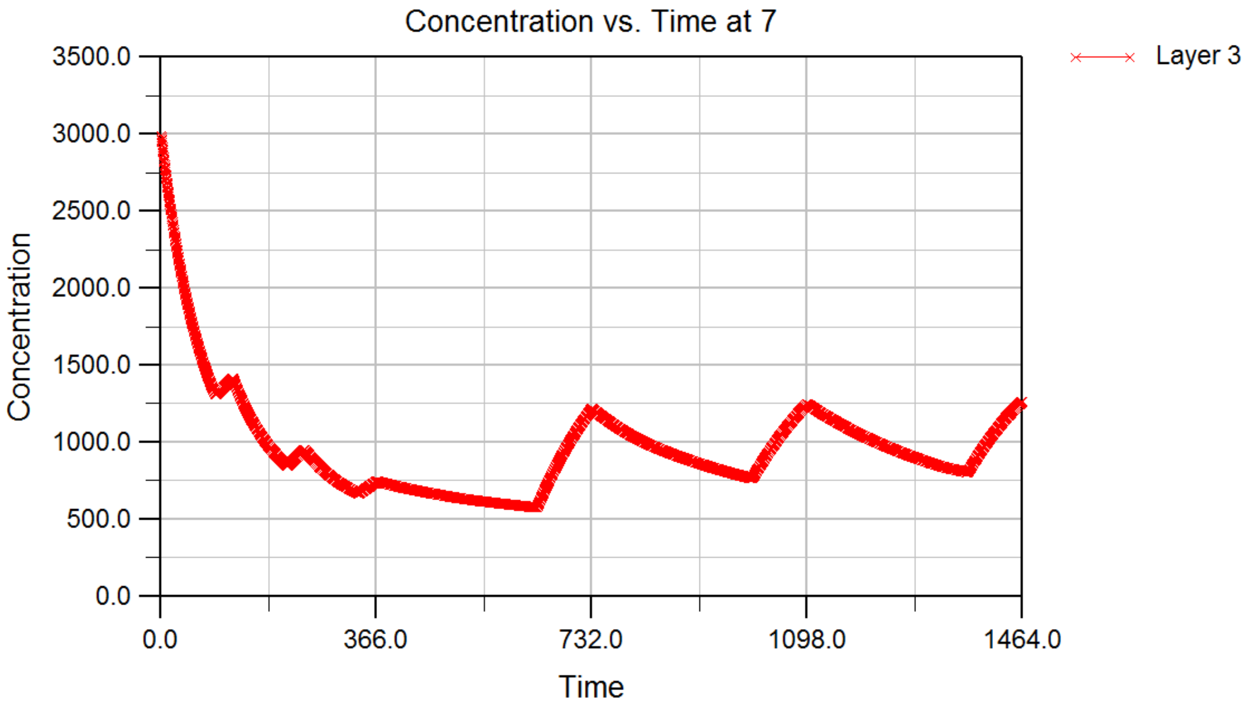
Concentration vs. Time at 3
Layer 3
Concentration
Time
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0

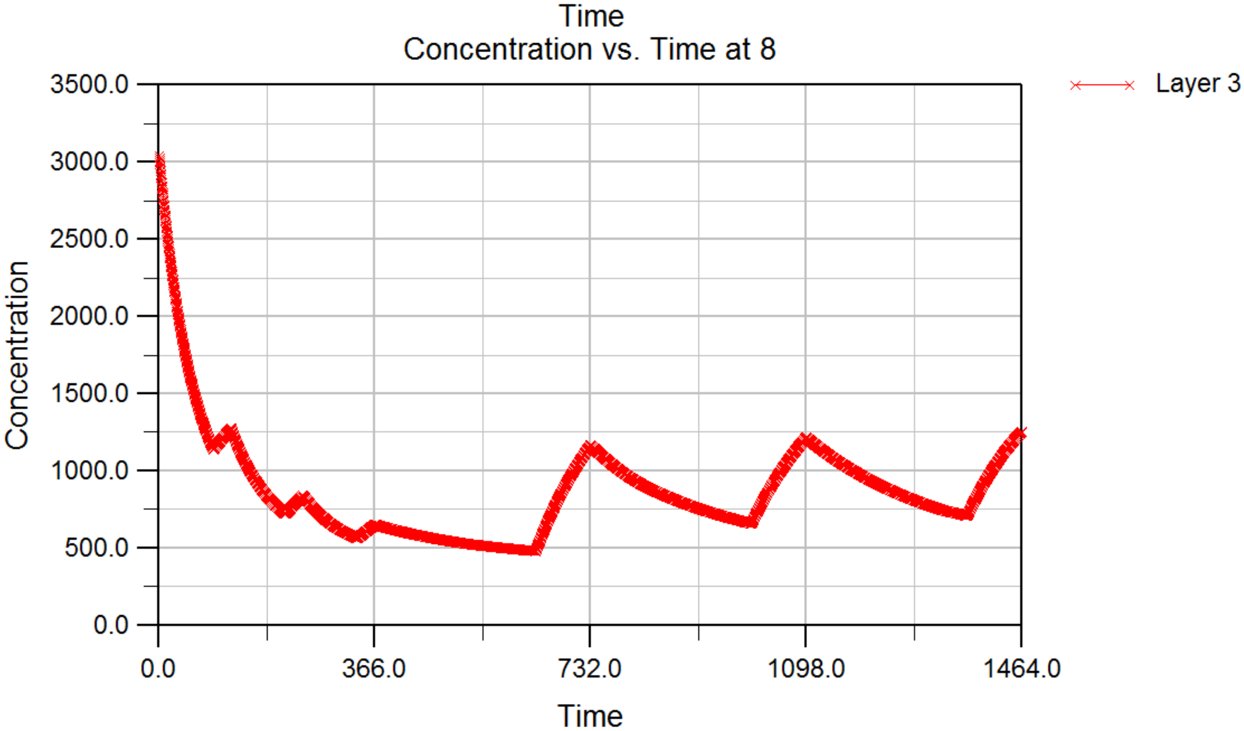


Concentration vs. Time at 4
Layer 3
Concentration
Time
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0

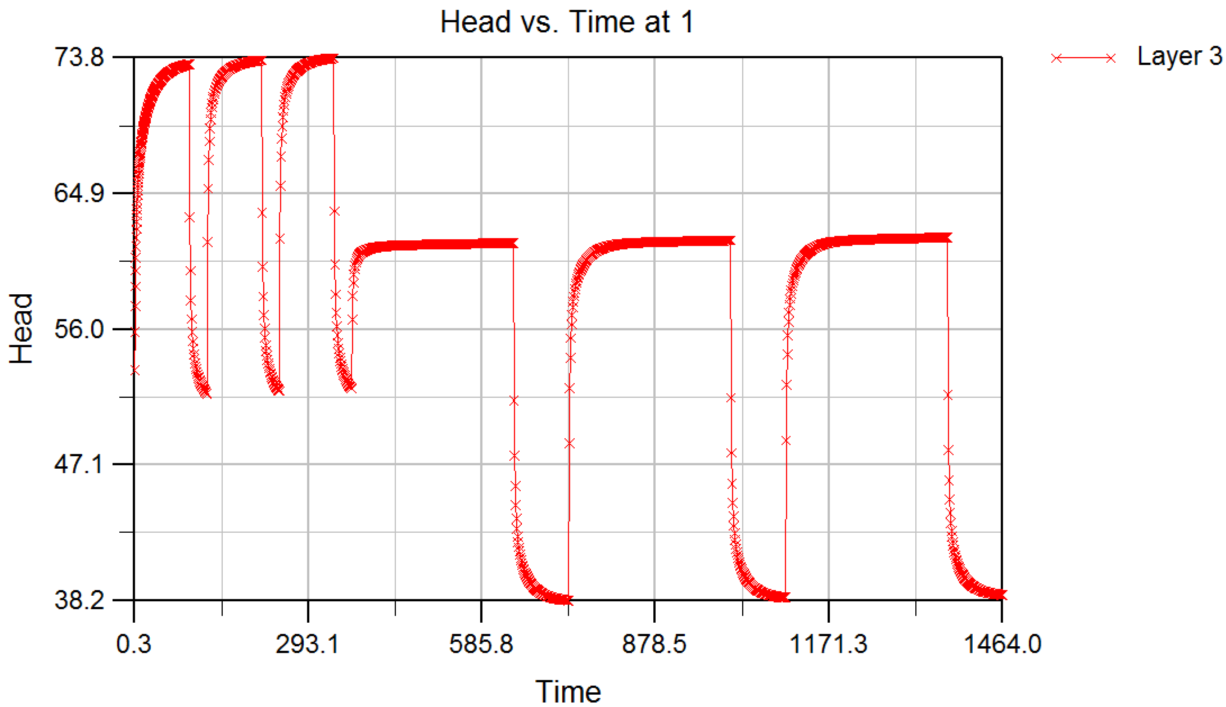

Concentration vs. Time at 5
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time

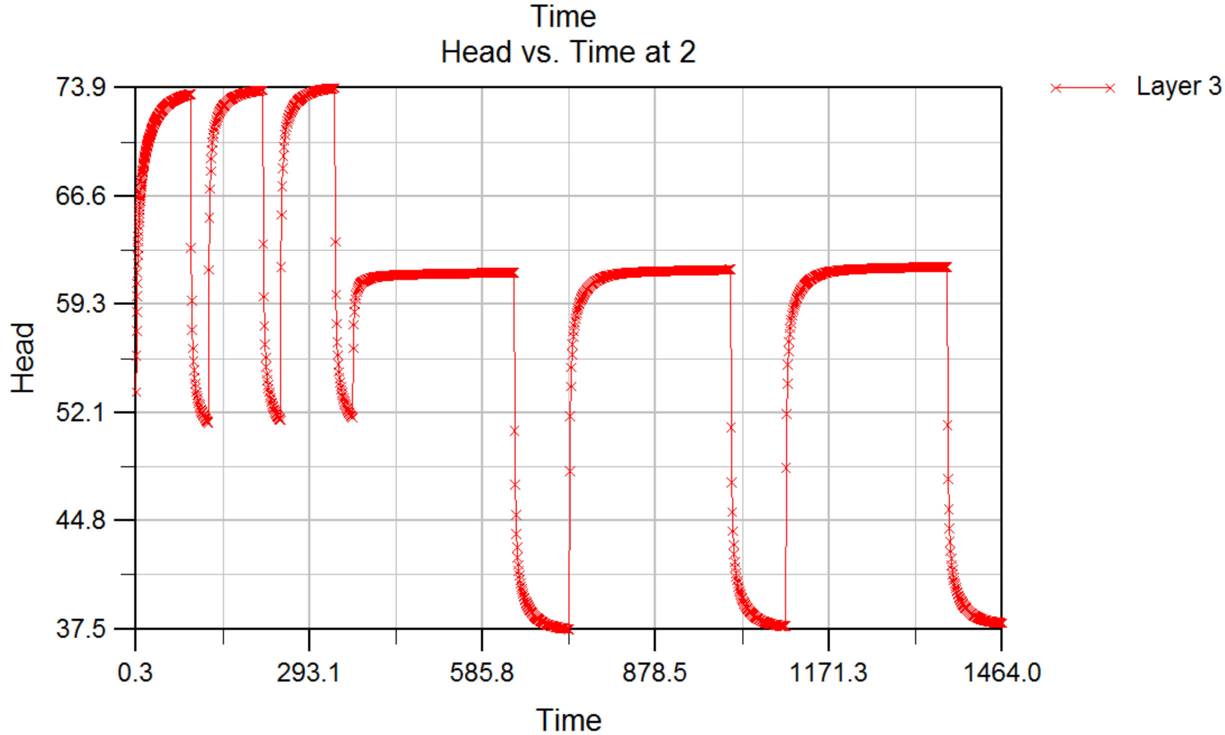

Concentration vs. Time at 6
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time

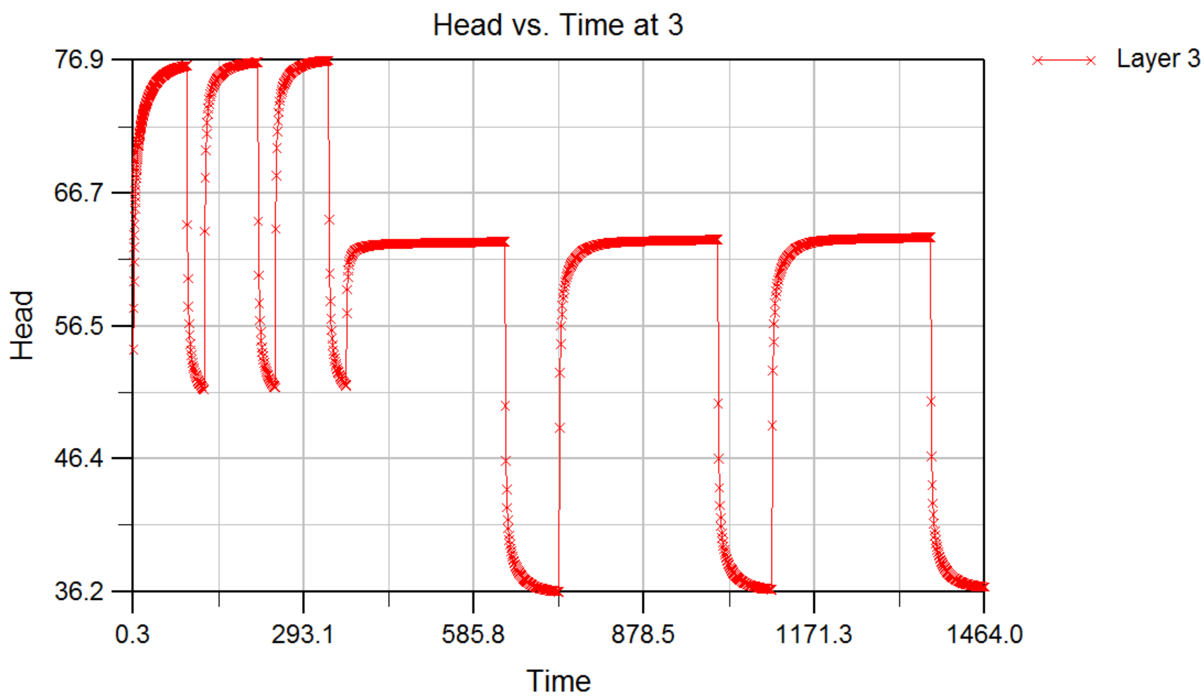

Concentration vs. Time at 7
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time

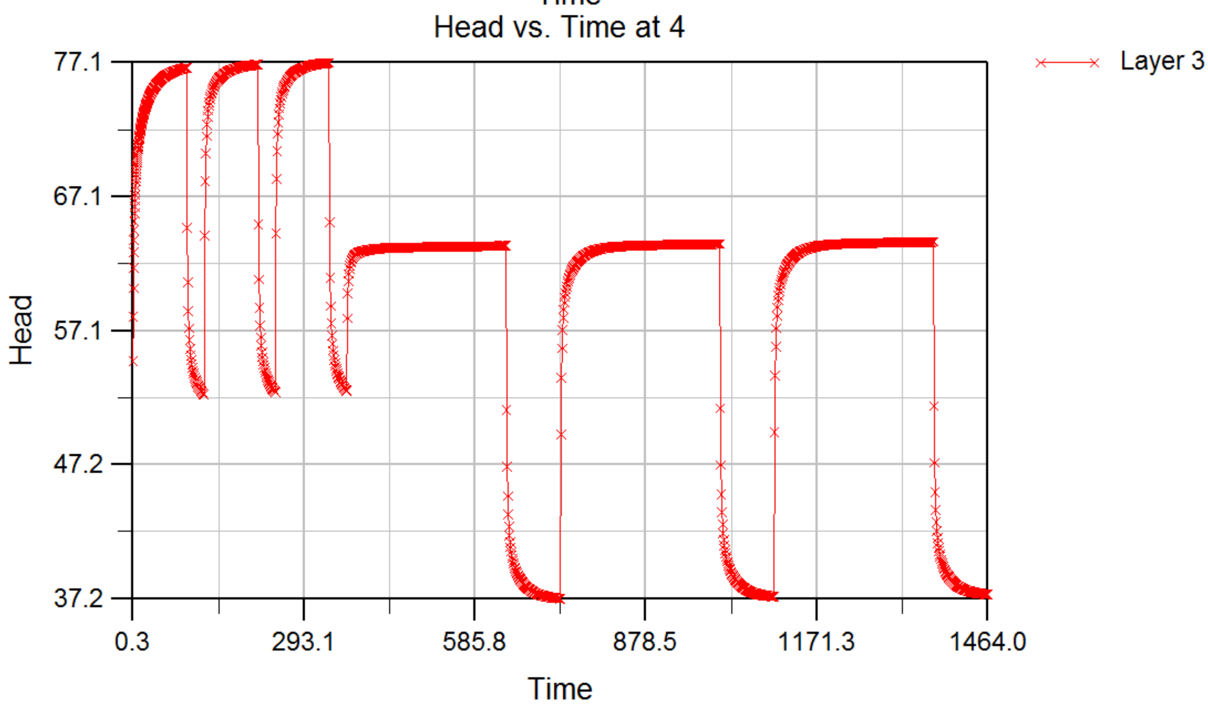

Concentration vs. Time at 8
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time

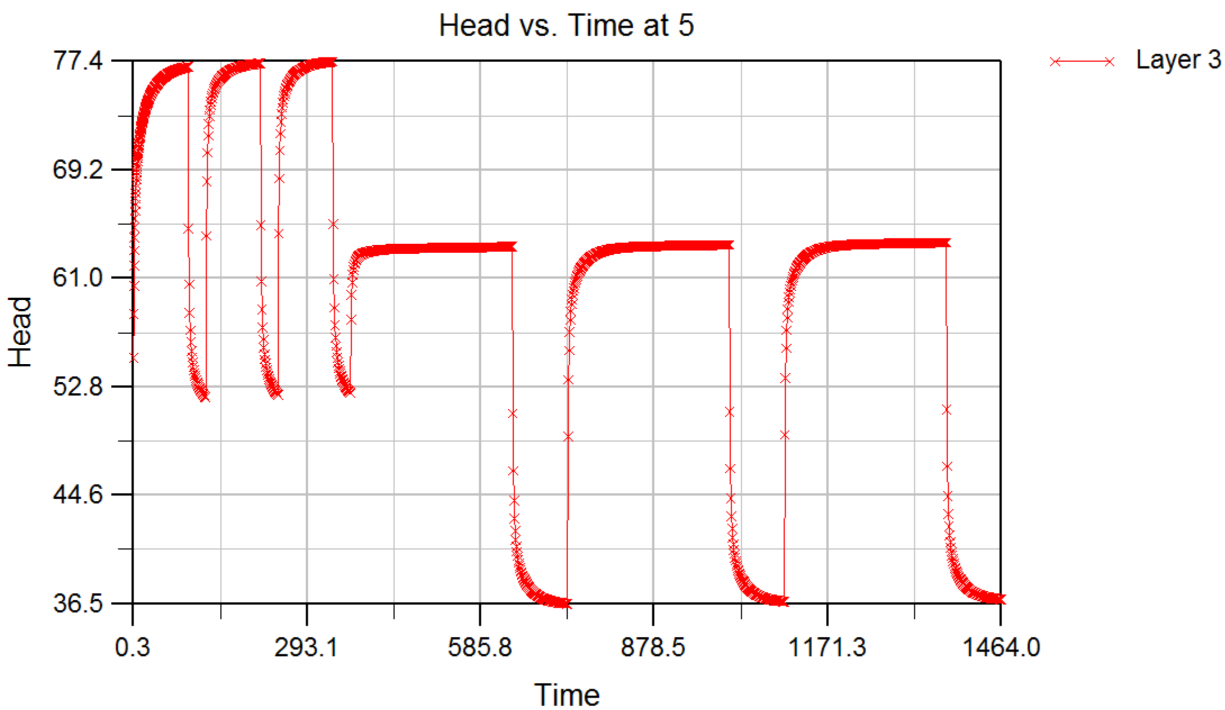
RUN 6 (MODFLOW & MT3D)

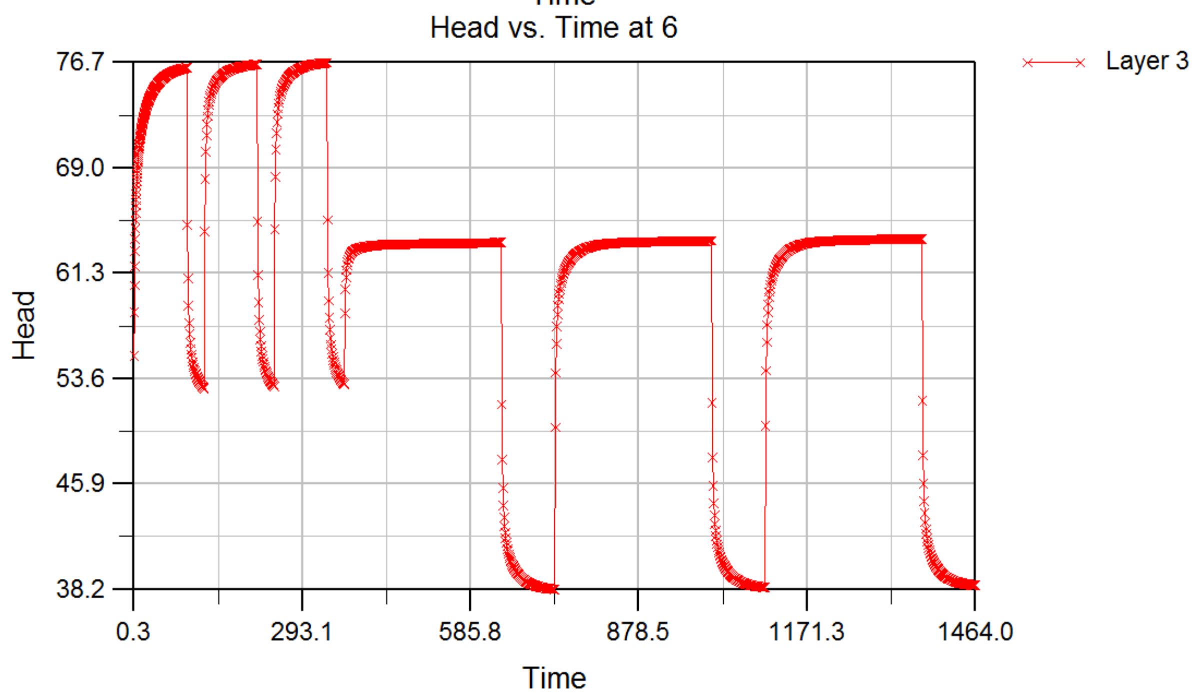


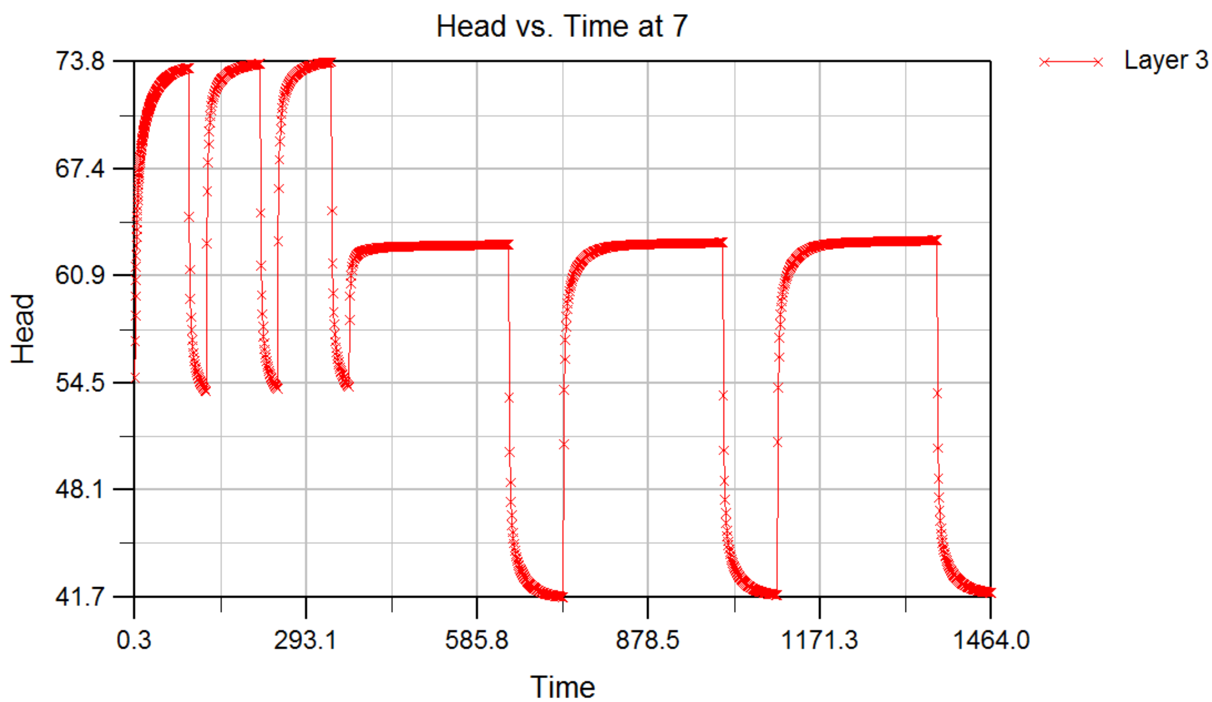



Head vs. Time at 3
Layer 3
76.9
66.7
56.5
46.4
36.2
Head
0.3
293.1
585.8
878.5
1171.3
1464.0
Time

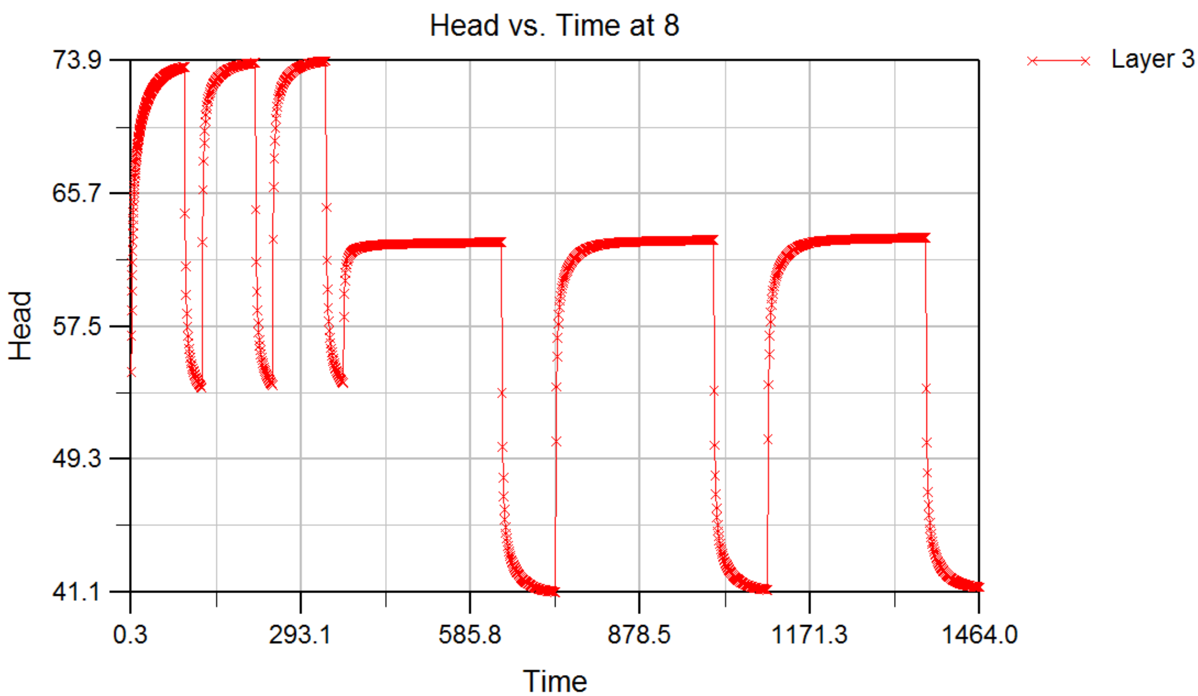

Head vs. Time at 4
Layer 3
77.1
67.1
57.1
47.2
37.2
Head
0.3
293.1
585.8
878.5
1171.3
1464.0
Time


Head vs. Time at 5
Layer 3
77.4
69.2
61.0
52.8
44.6
36.5
Head
0.3
293.1
585.8
878.5
1171.3
1464.0
Time

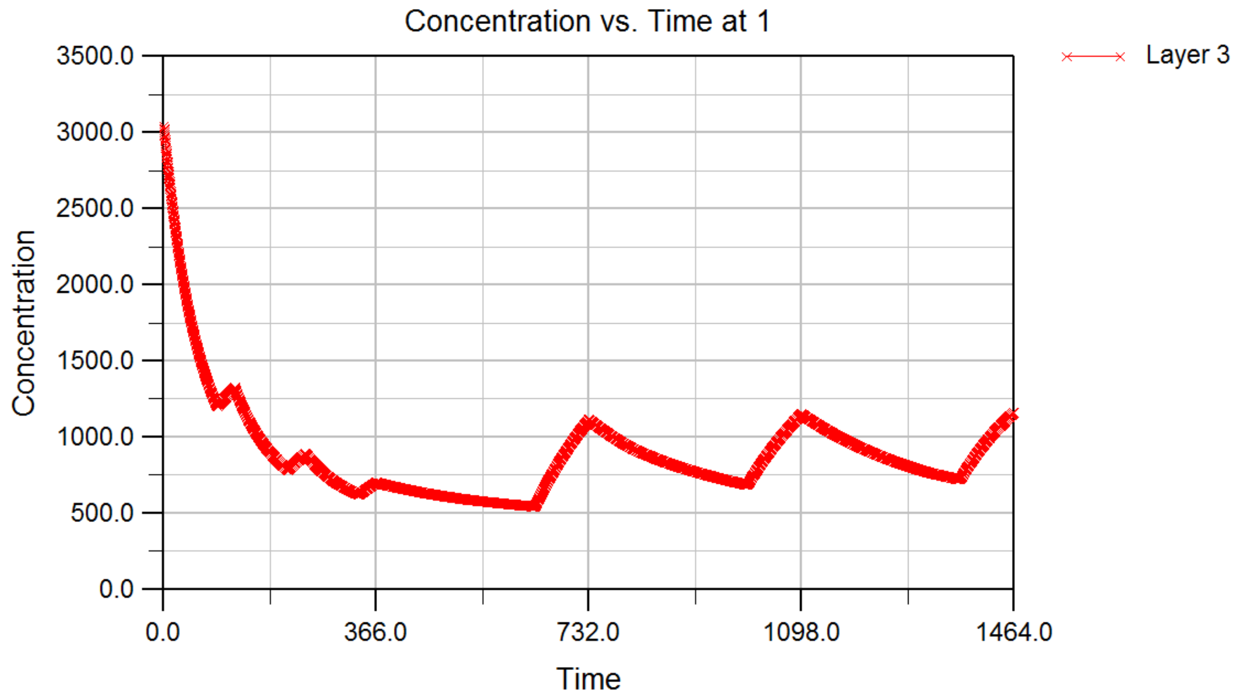

Head vs. Time at 6
Layer 3
76.7
69.0
61.3
53.6
45.9
38.2
Head
0.3
293.1
585.8
878.5
1171.3
1464.0
Time

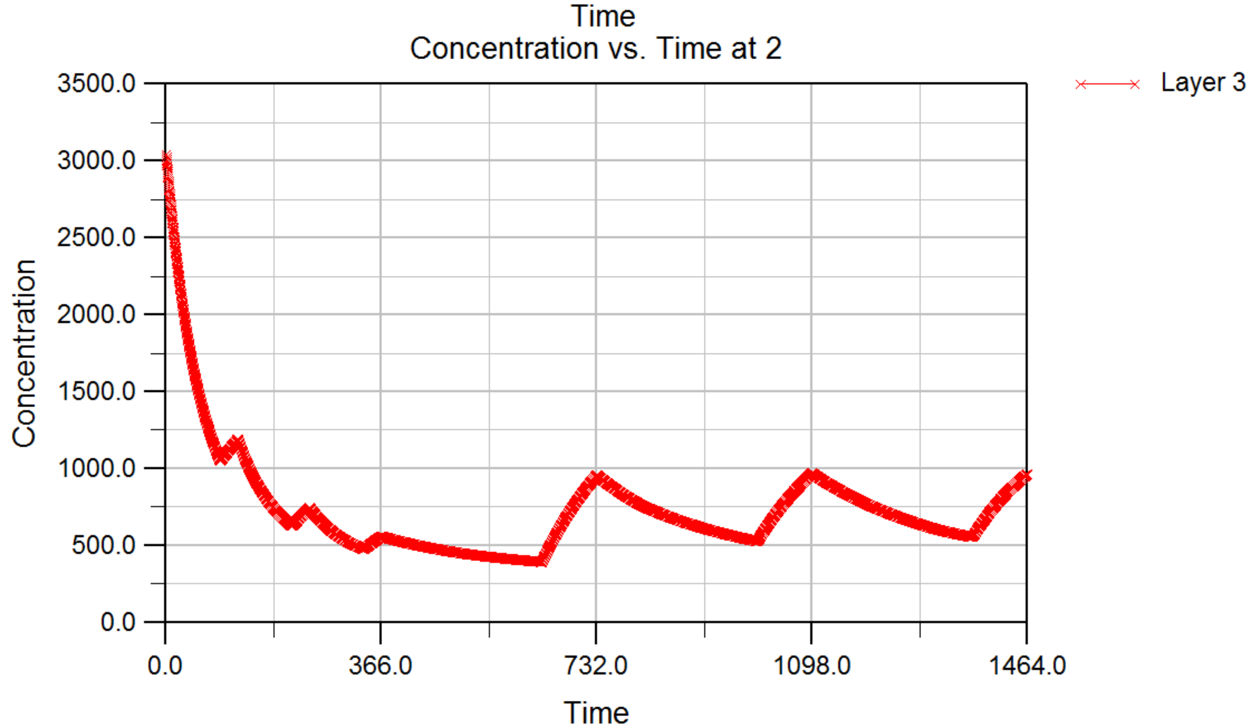


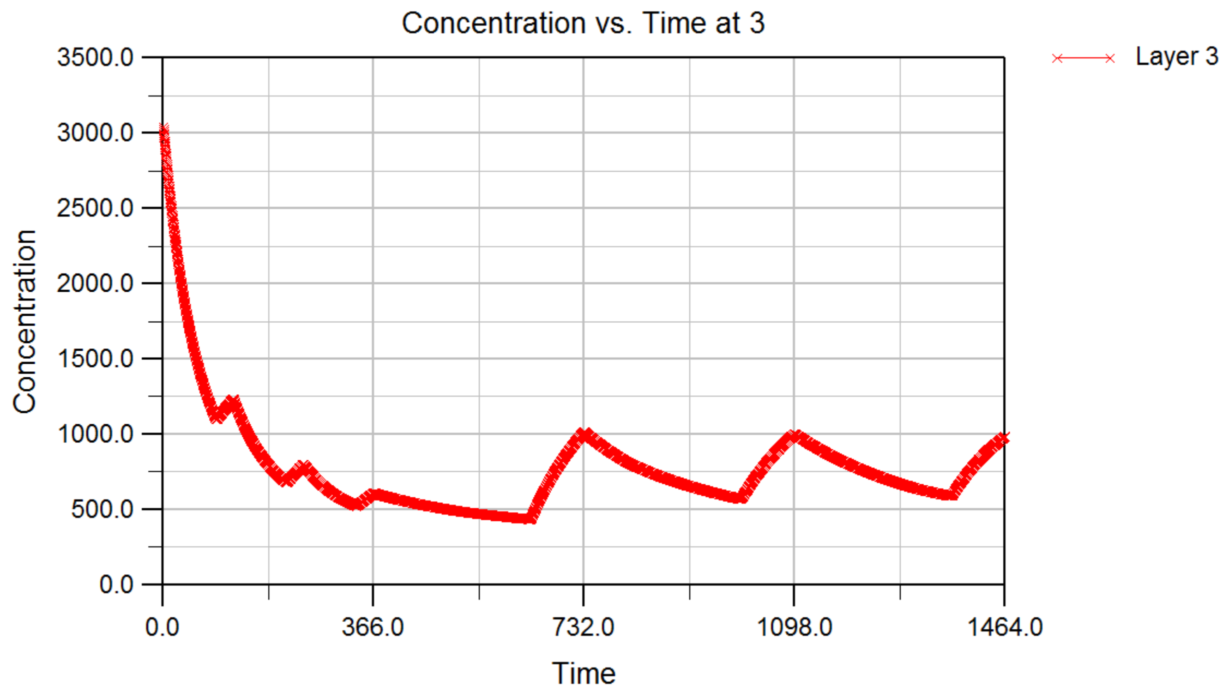
Head vs. Time at 7
Layer 3
73.8
67.4
60.9
54.5
48.1
41.7
Head
0.3
293.1
585.8
878.5
1171.3
1464.0
Time

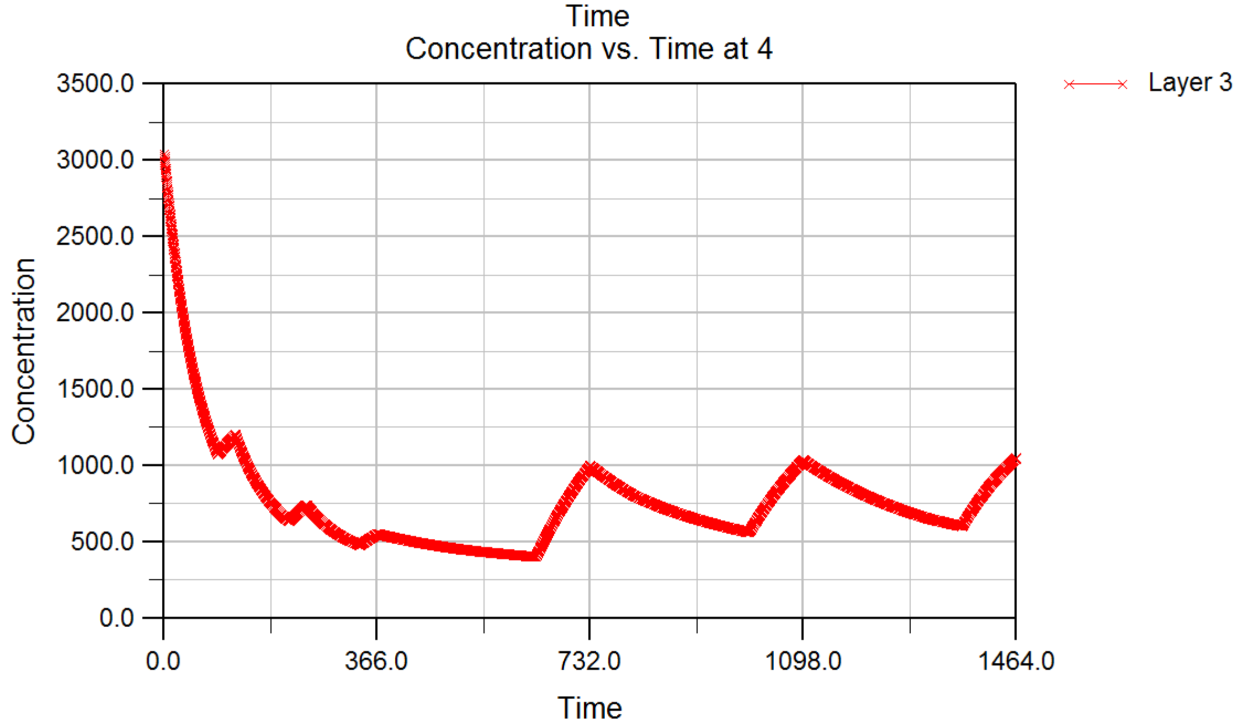


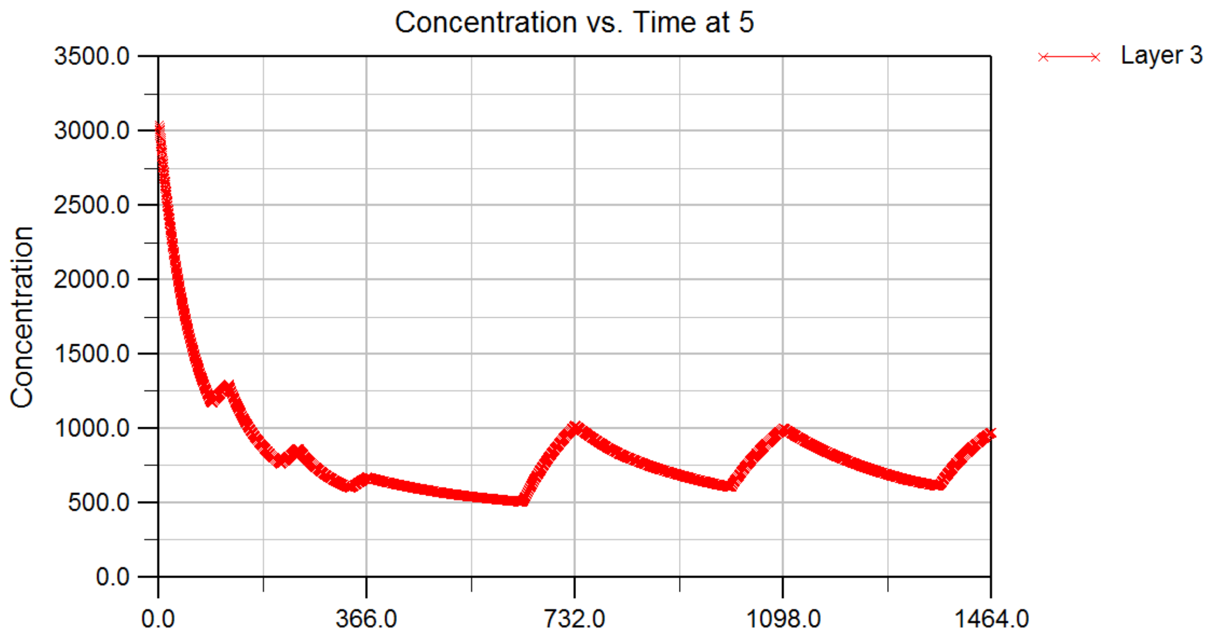
Head vs. Time at 8
Layer 3
73.9
65.7
57.5
49.3
41.1
Head
0.3
293.1
585.8
878.5
1171.3
1464.0
Time

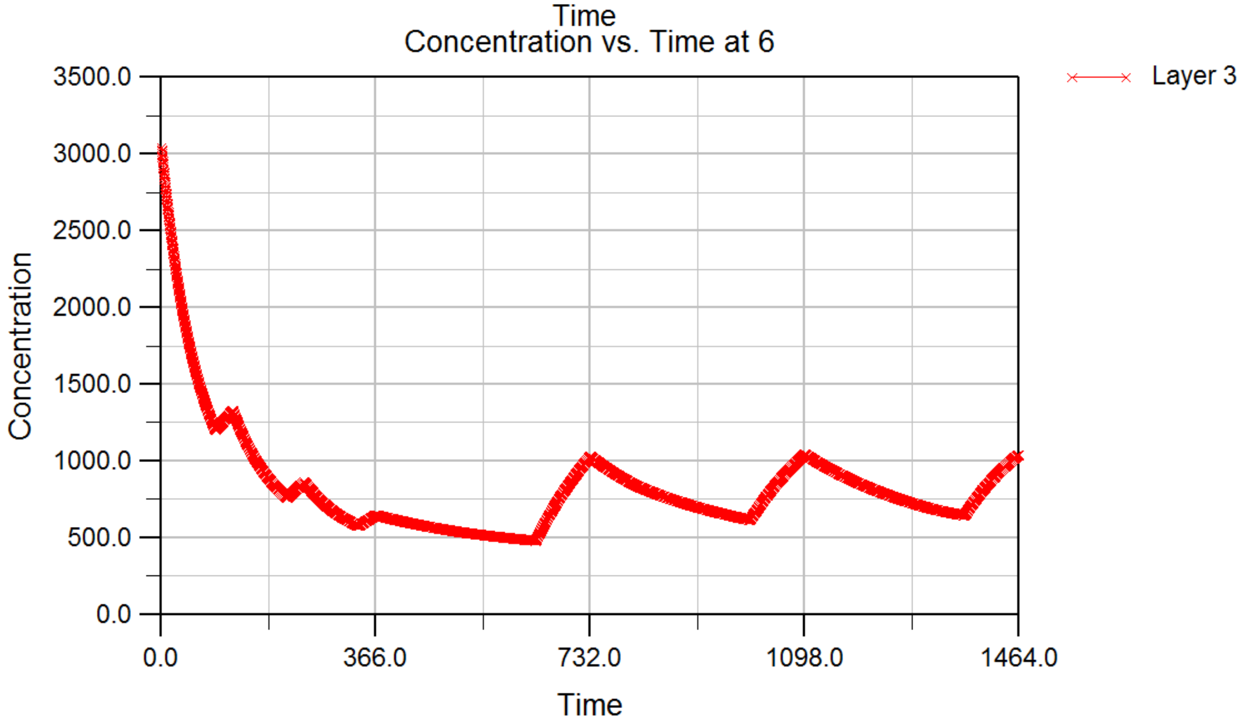

Concentration vs. Time at 1
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time

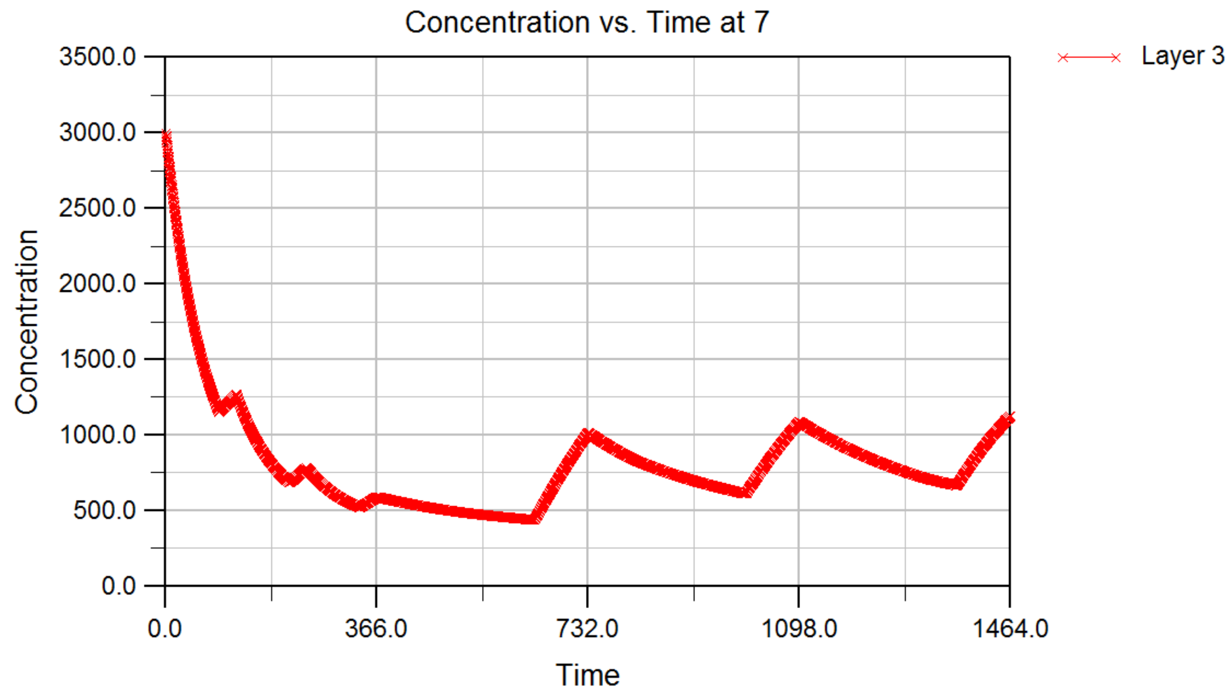

Concentration vs. Time at 2
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time

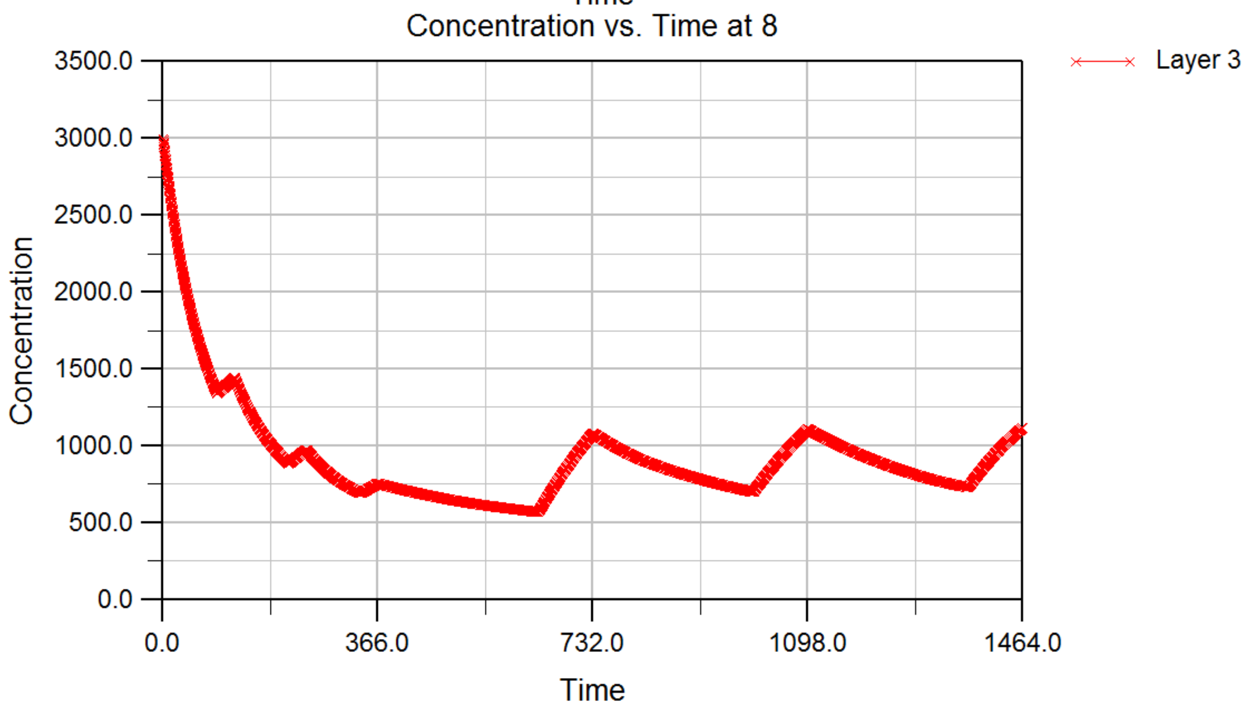

Concentration vs. Time at 3
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time


Concentration vs. Time at 4
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time

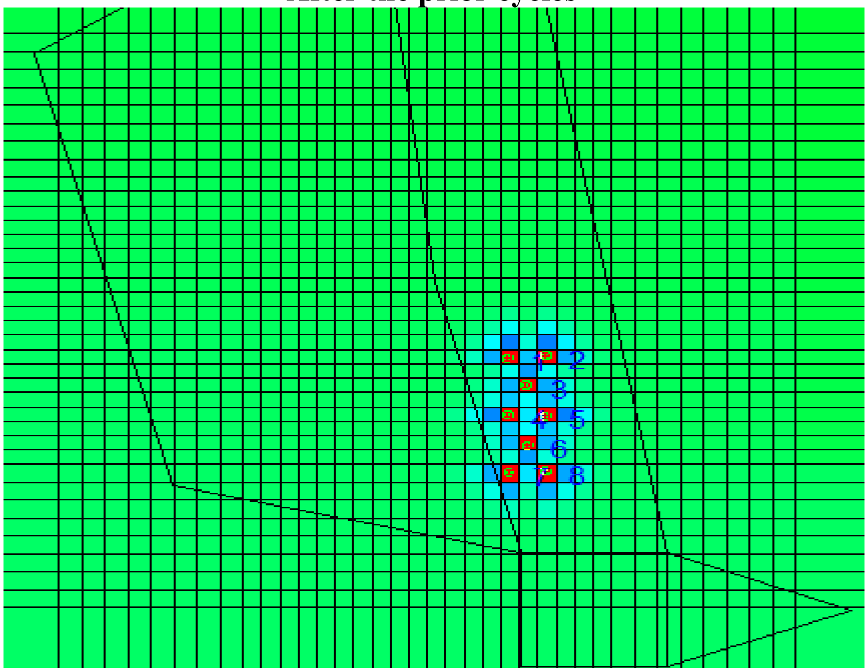

Concentration vs. Time at 5
Layer 3
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
Concentration
0.0
366.0
732.0
1098.0
1464.0
Time


Concentration vs. Time at 6
Layer 3
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
Concentration
0.0
366.0
732.0
1098.0
1464.0
Time

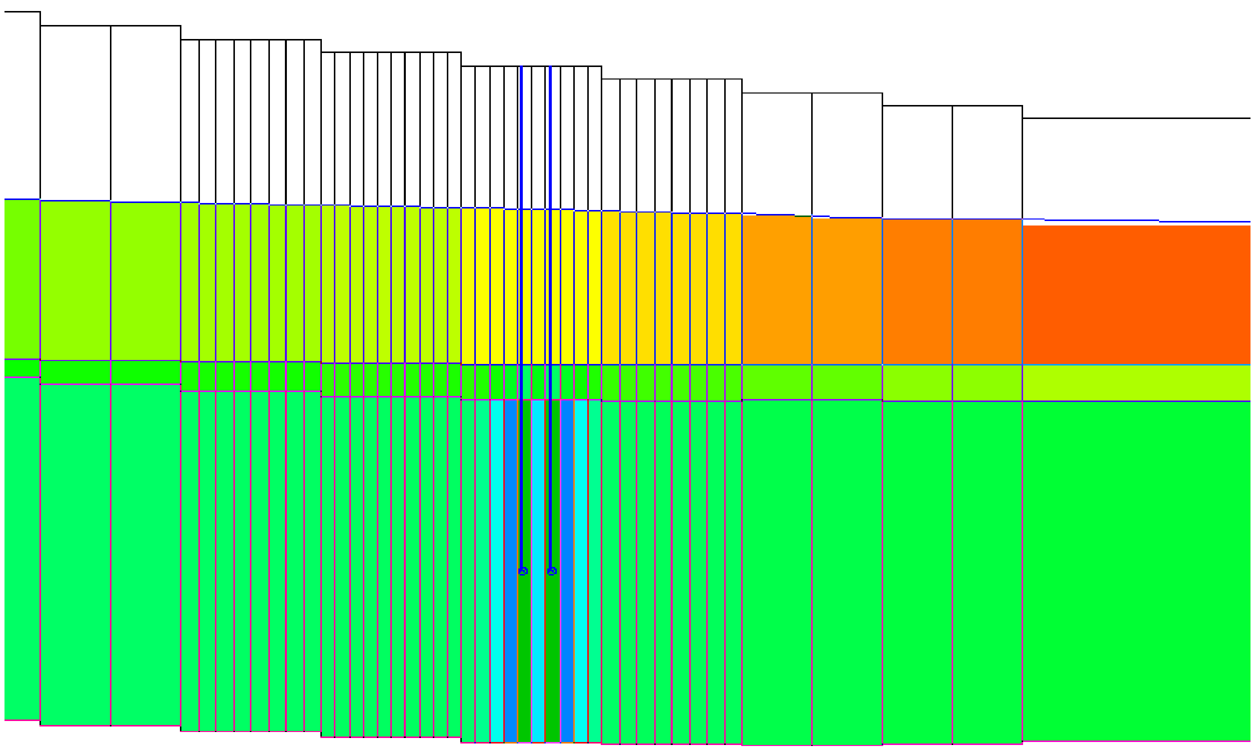

Concentration vs. Time at 7
Layer 3
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
Concentration
0.0
366.0
732.0
1098.0
1464.0
Time


Concentration vs. Time at 8
Layer 3
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
Concentration
0.0
366.0
732.0
1098.0
1464.0
Time

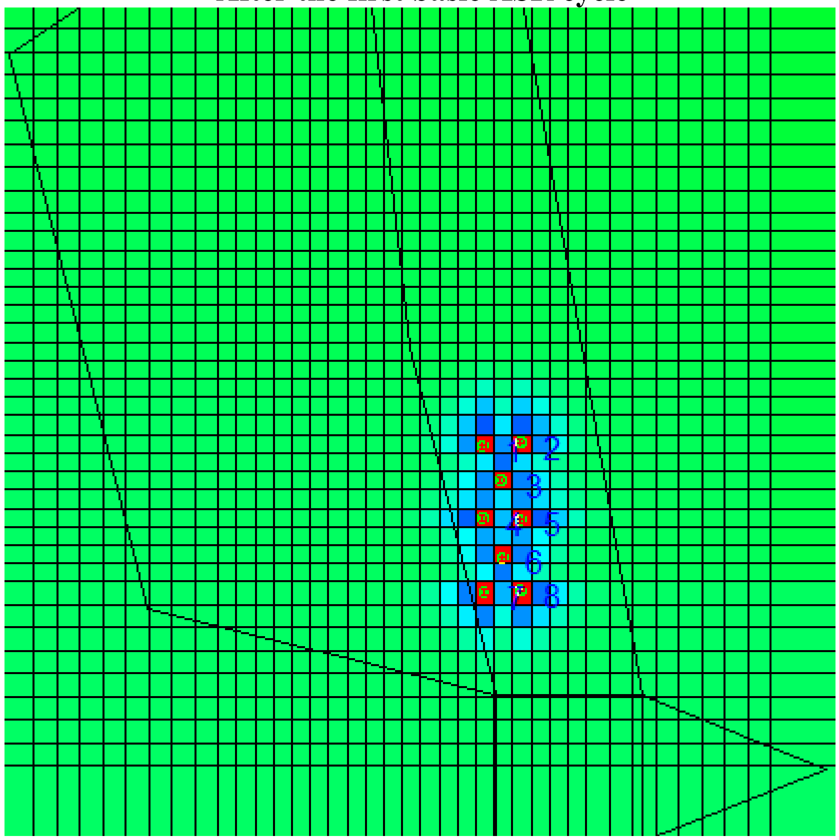
After the prior cycles



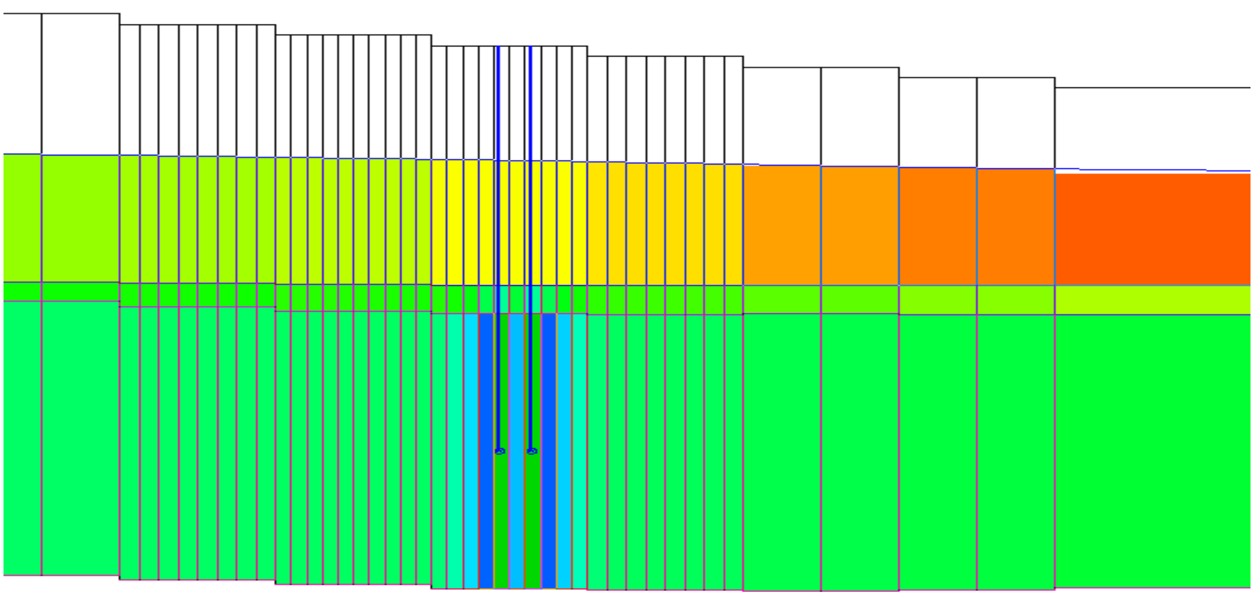
Cross-Section along Row 30



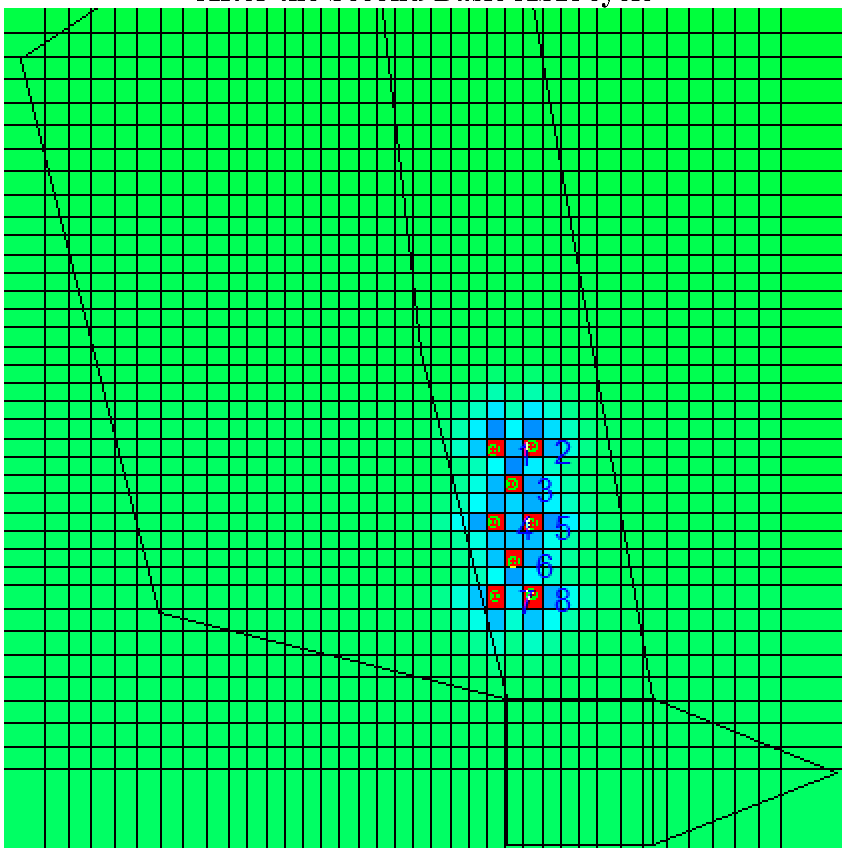
After the first basic ASR cycle



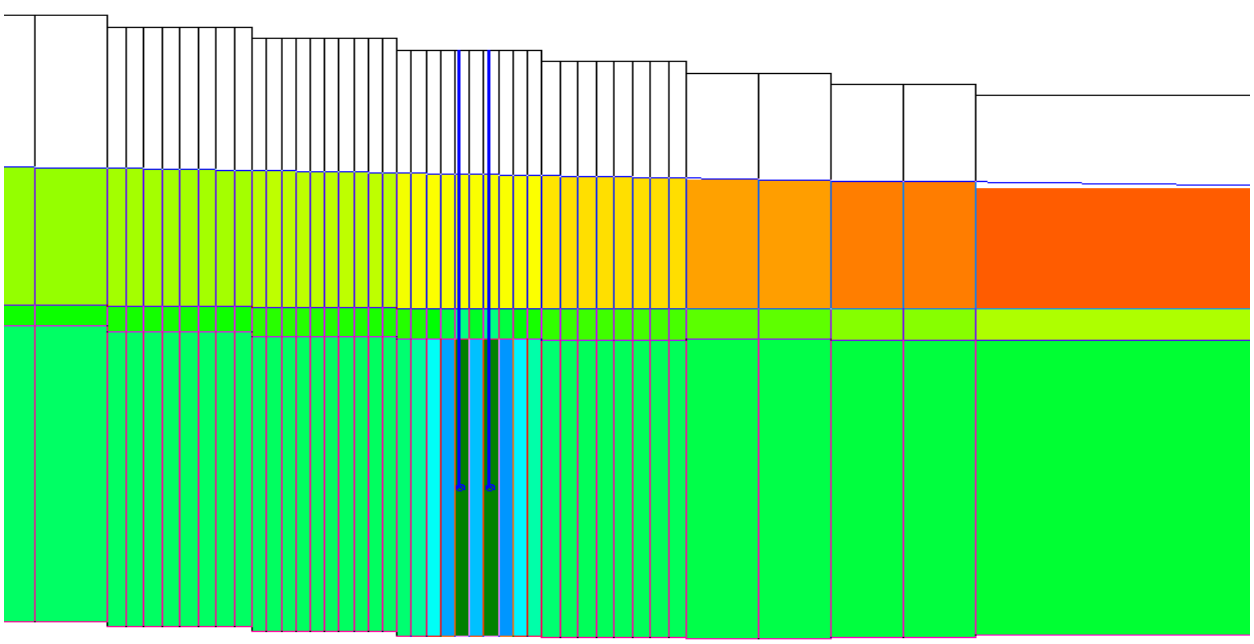
Cross-Section along Row 30



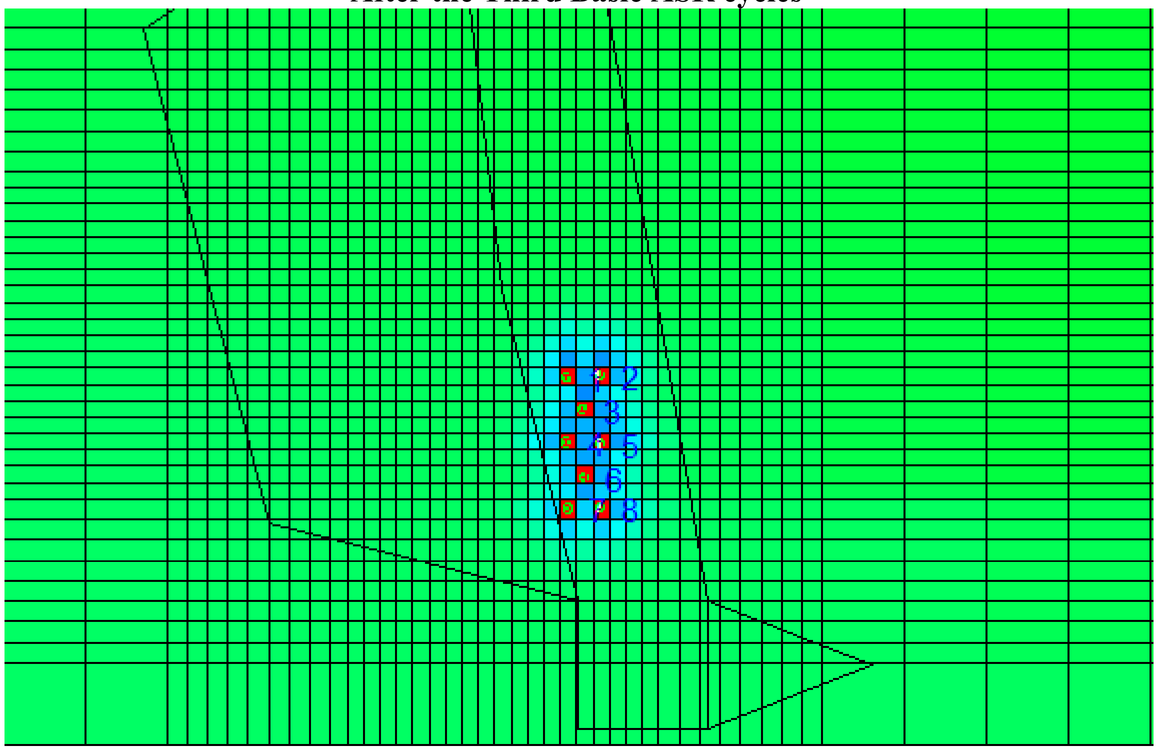
After the Second Basic ASR cycle



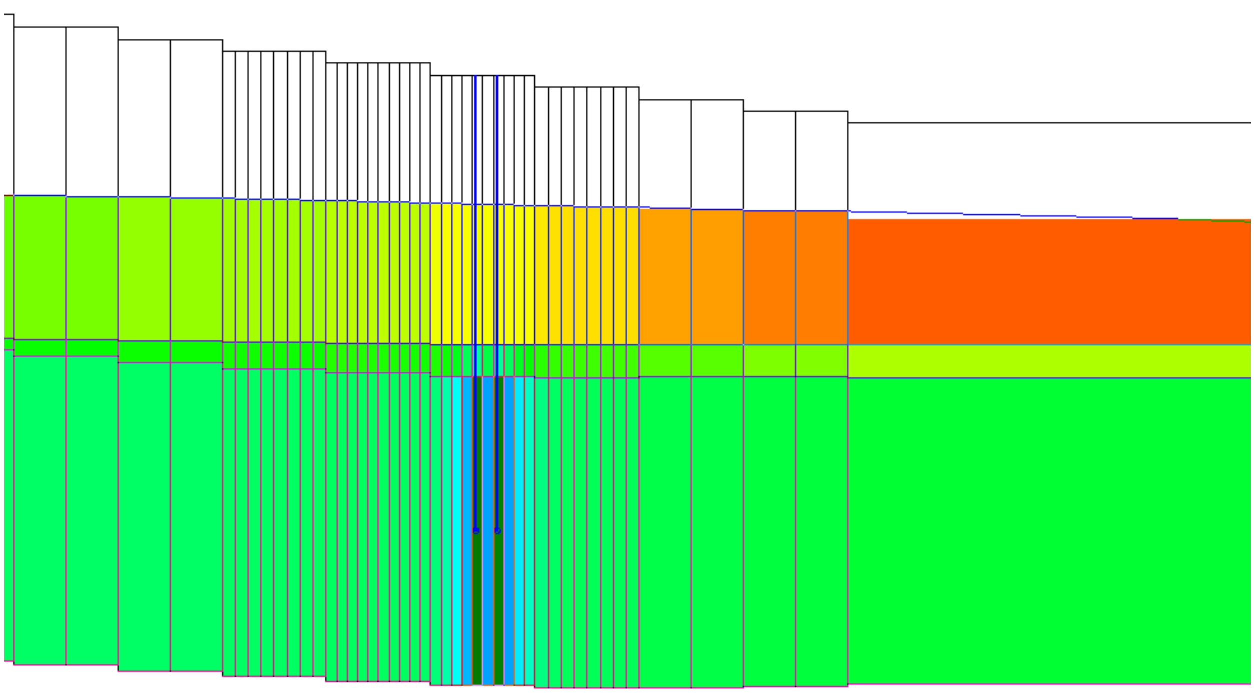
Cross-Section along Row 30



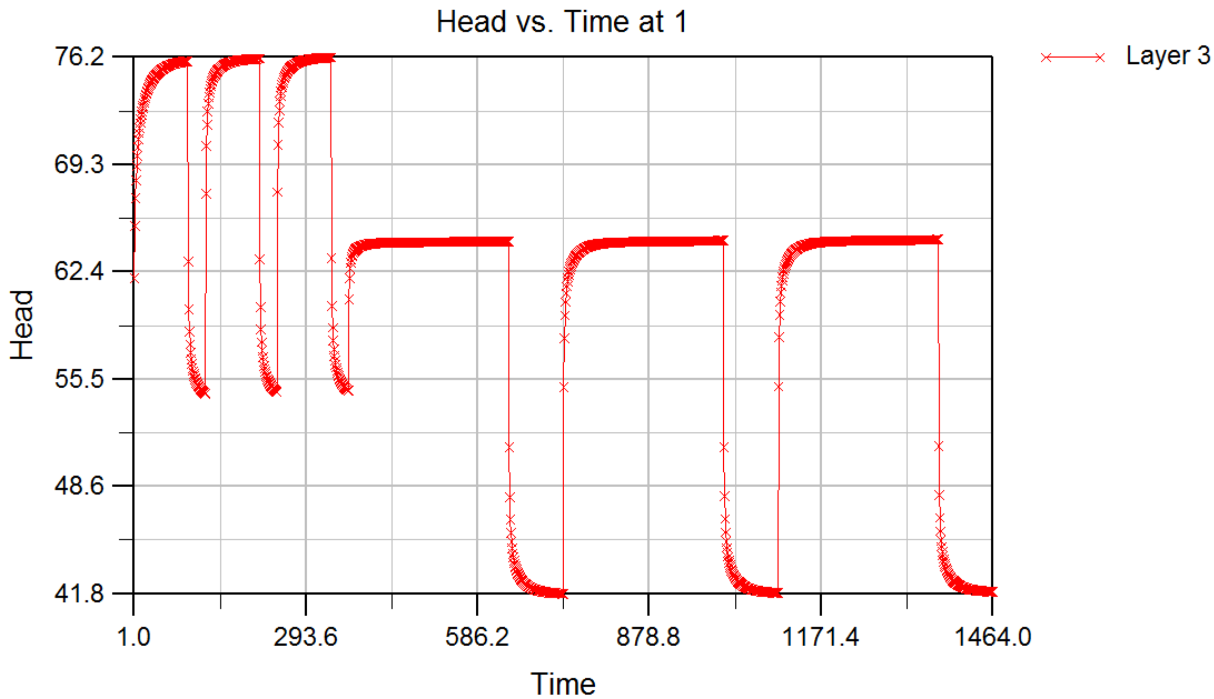
After the Third Basic ASR cycles

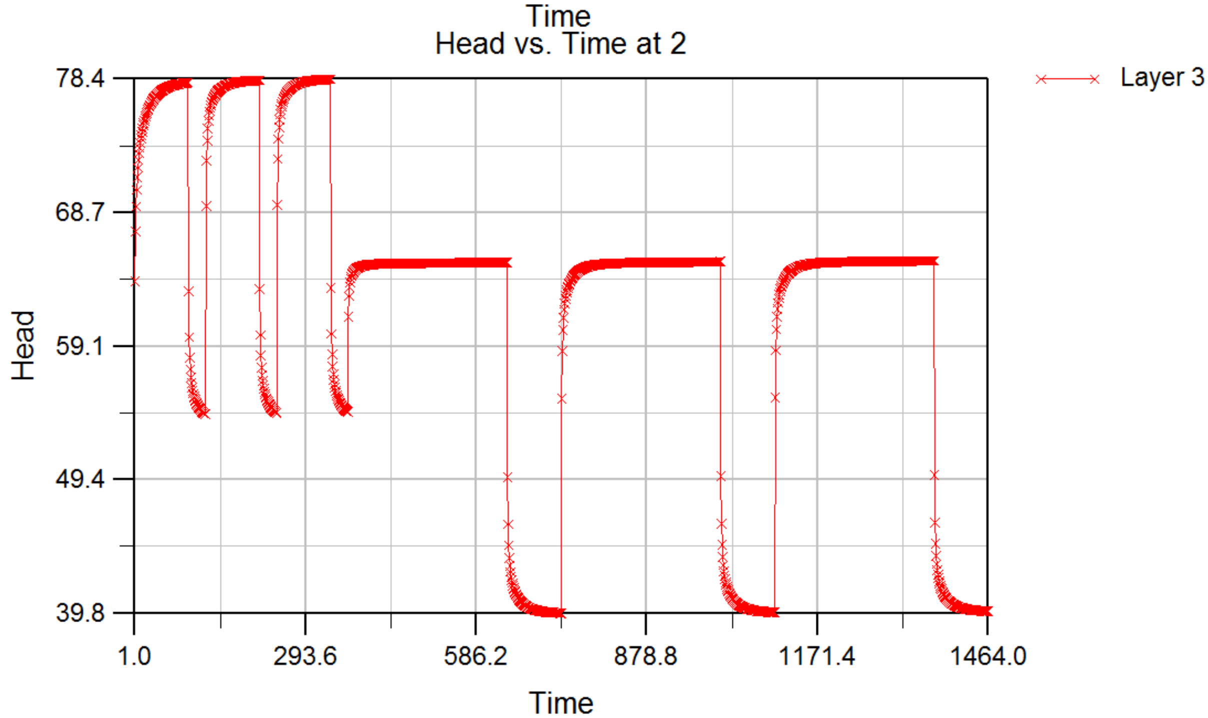


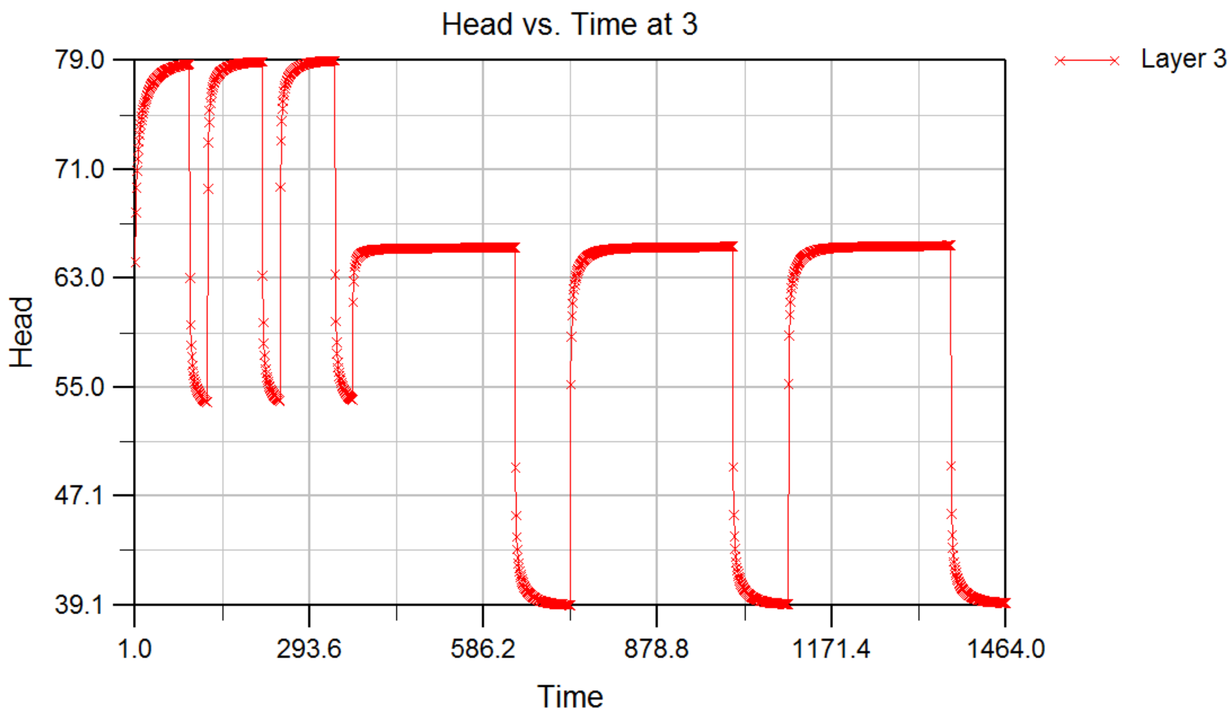
Cross-Section along Row 30

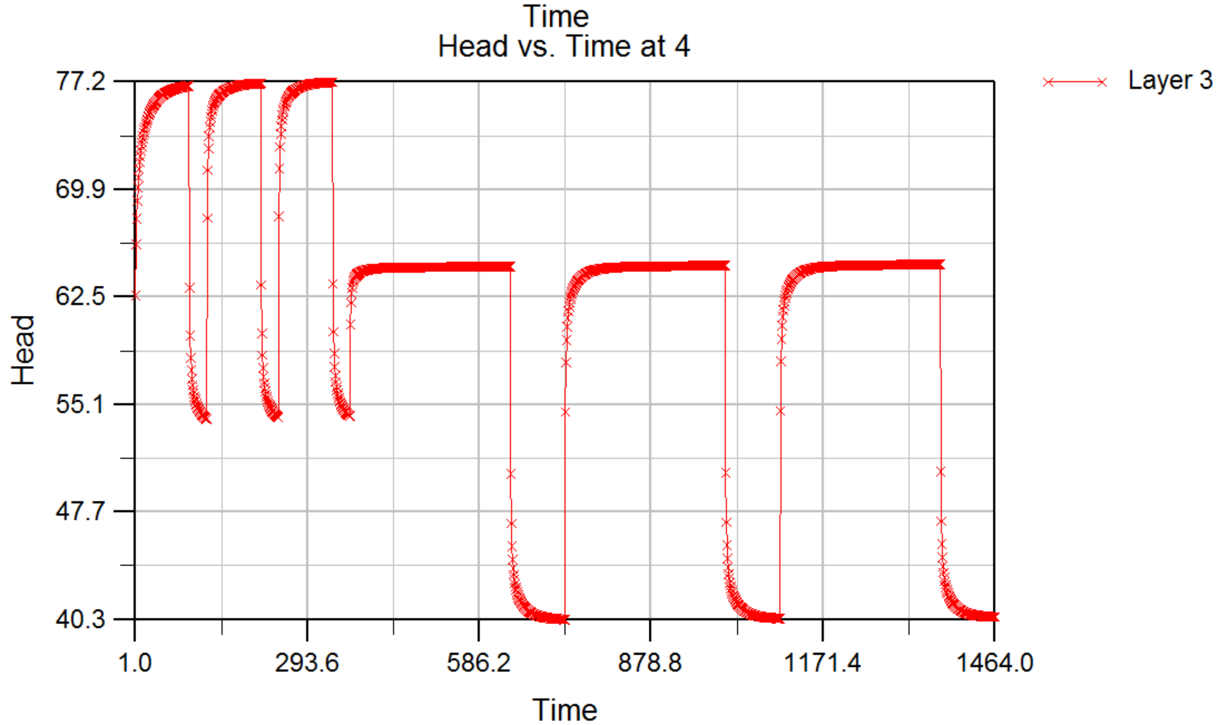


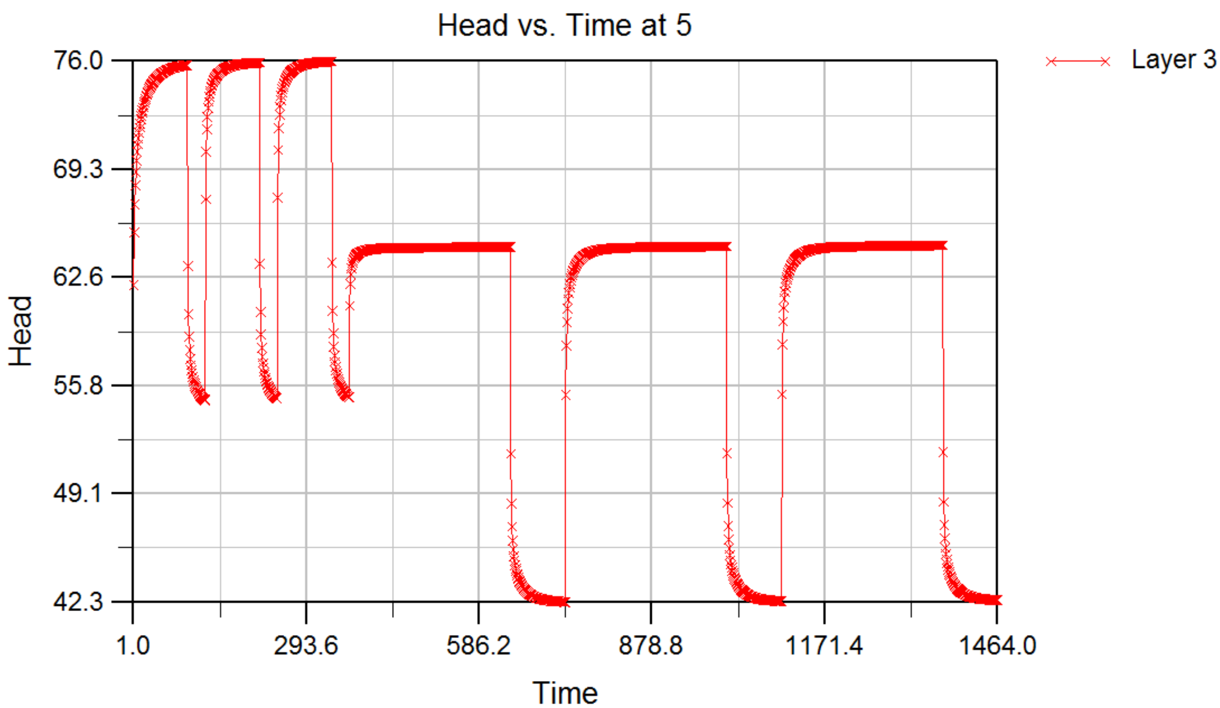
RUN 7 MODFLOW

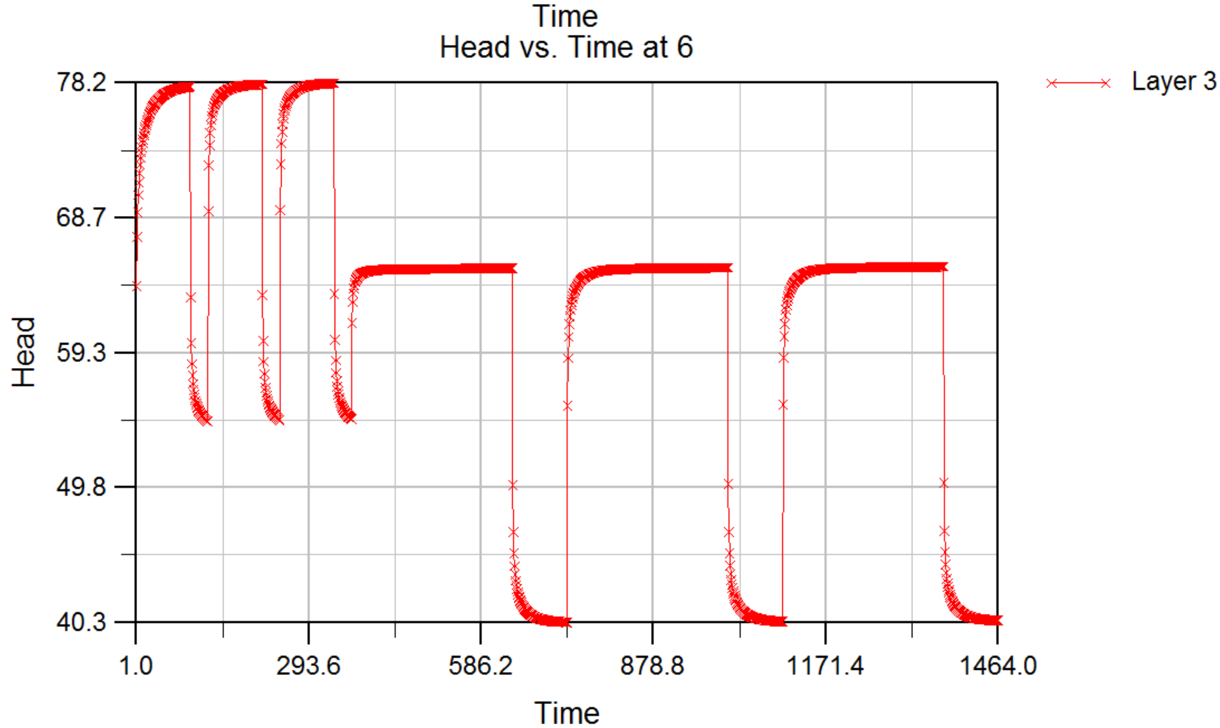


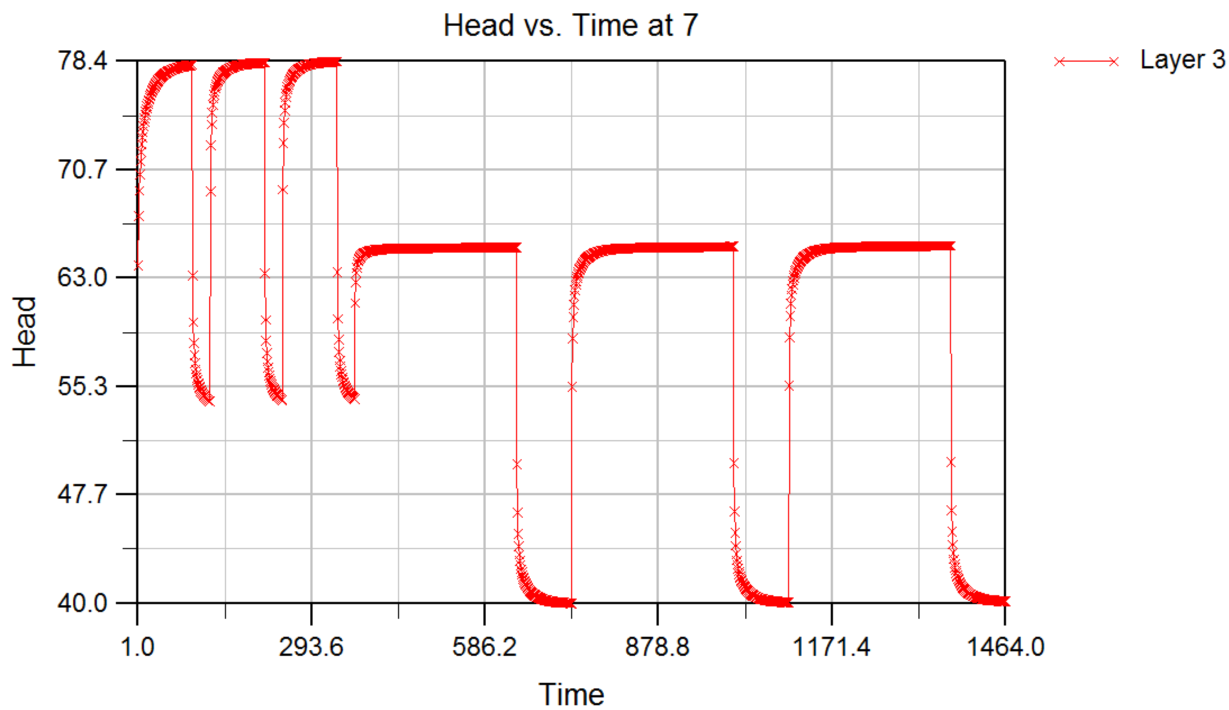


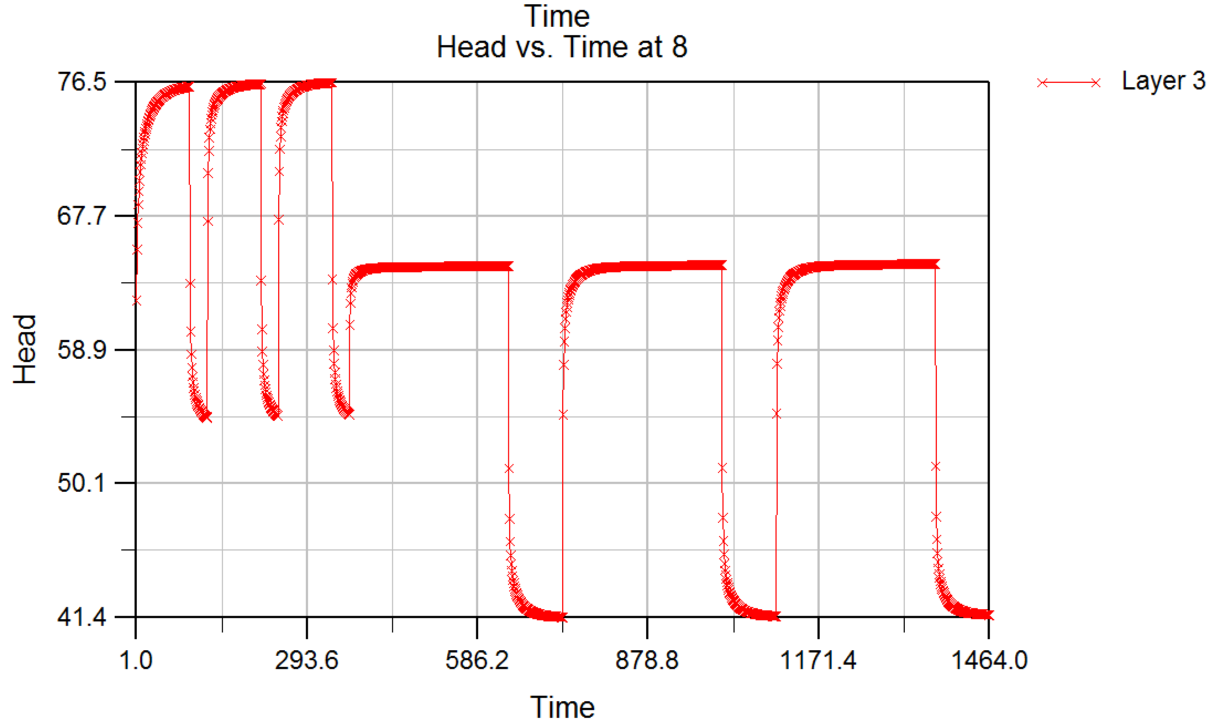

Head vs. Time at 3
Layer 3
79.0
71.0
63.0
55.0
47.1
39.1
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time


Head vs. Time at 4
Layer 3
77.2
69.9
62.5
55.1
47.7
40.3
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time


Head vs. Time at 5
Layer 3
76.0
69.3
62.6
55.8
49.1
42.3
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

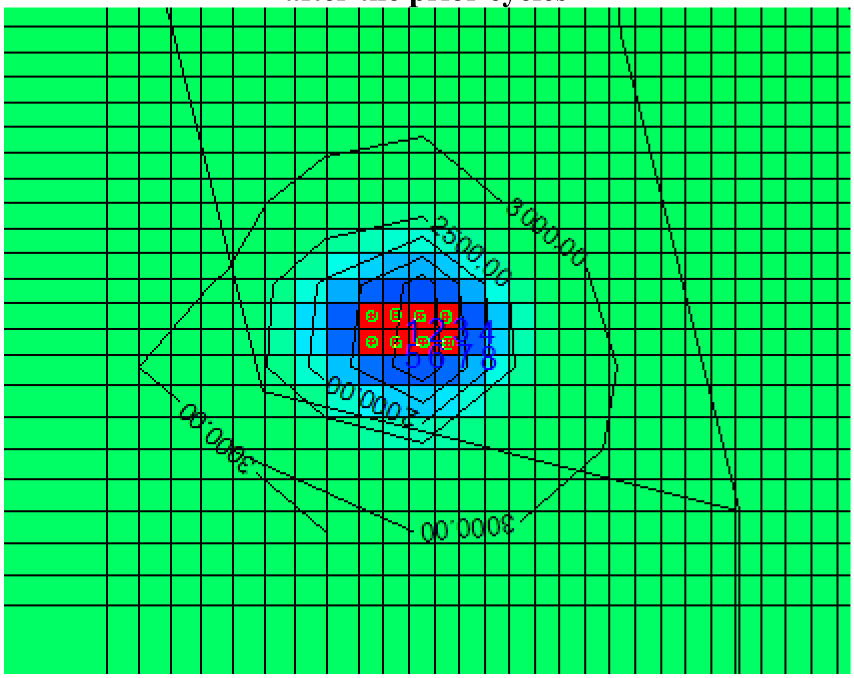

Head vs. Time at 6
Layer 3
78.2
68.7
59.3
49.8
40.3
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time


Head vs. Time at 7
Layer 3
78.4
70.7
63.0
55.3
47.7
40.0
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

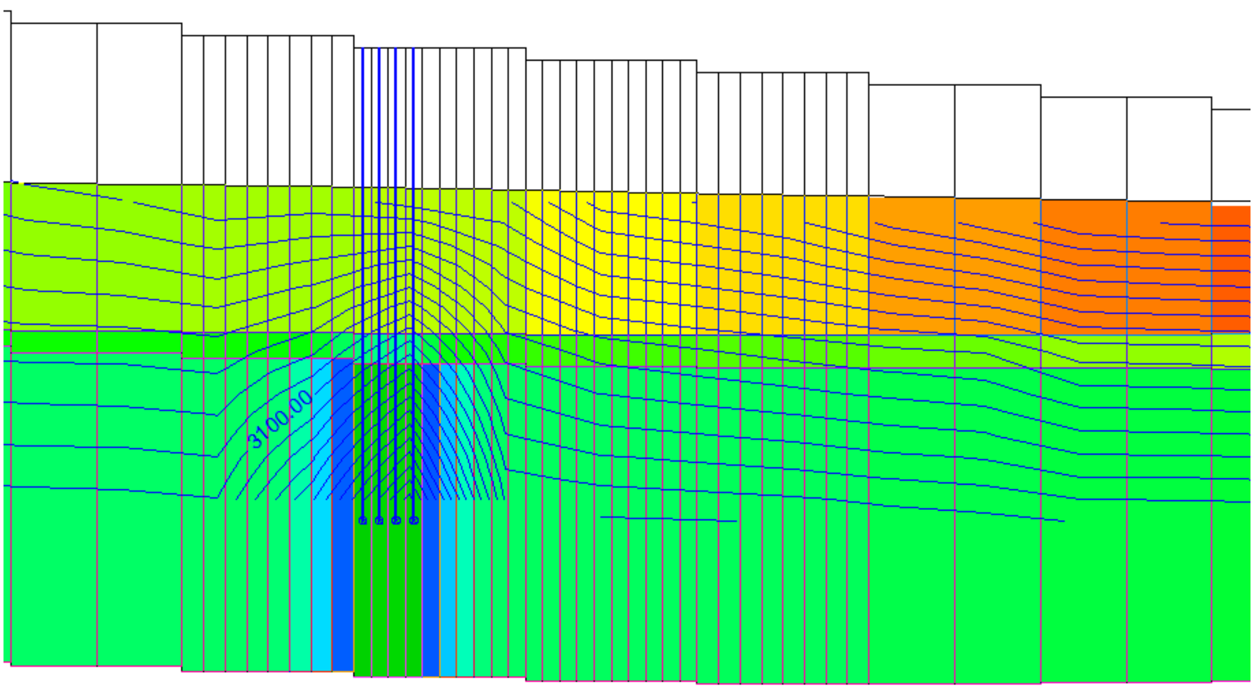

Head vs. Time at 8
Layer 3
76.5
67.7
58.9
50.1
41.4
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

RUN 7   MT3D

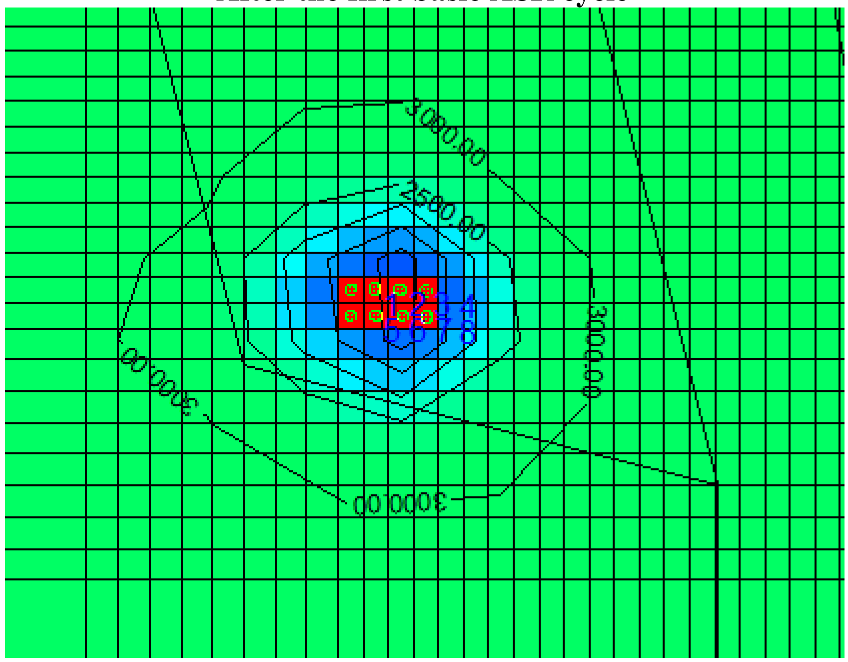
after the prior cycles



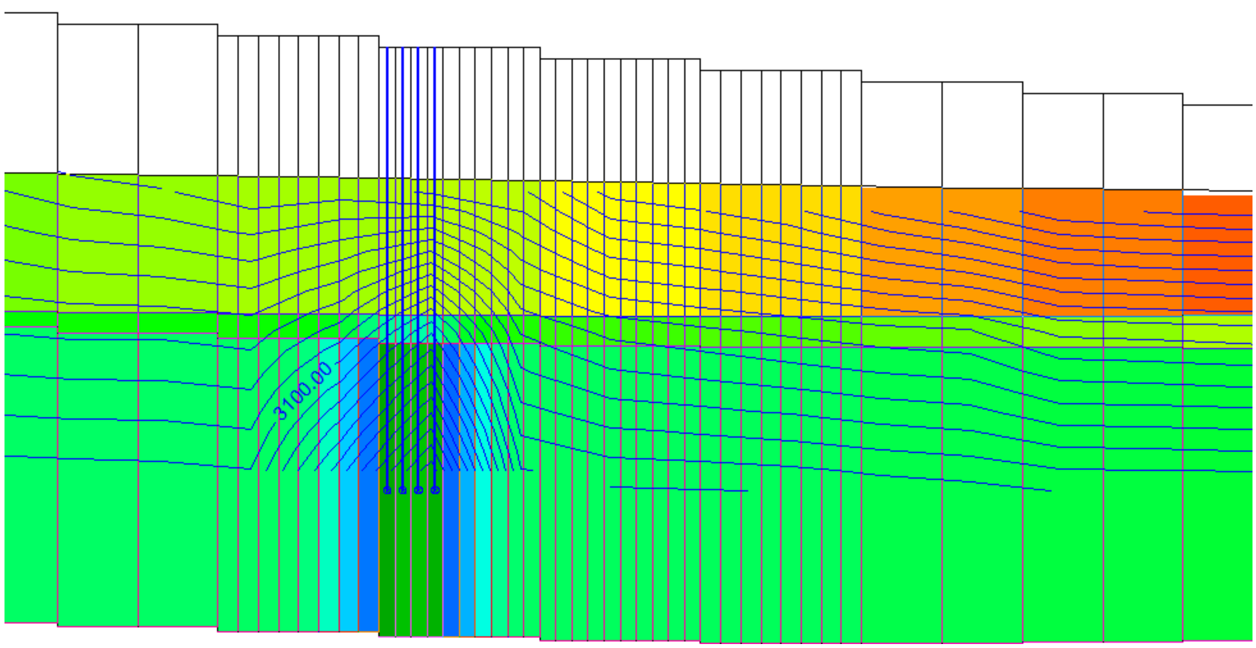
Cross-Section along Row 32



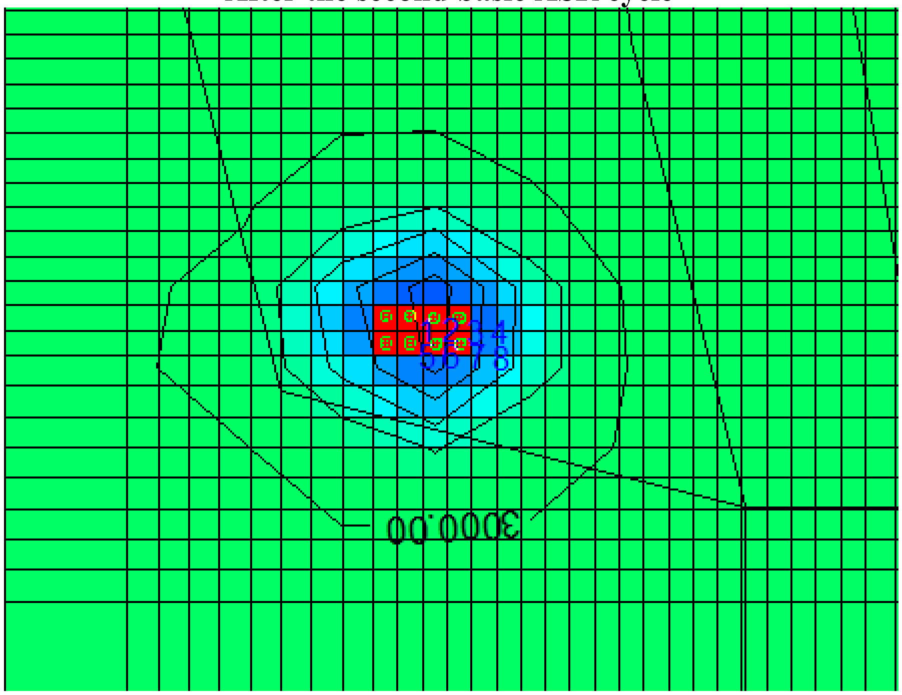
After the first basic ASR cycle



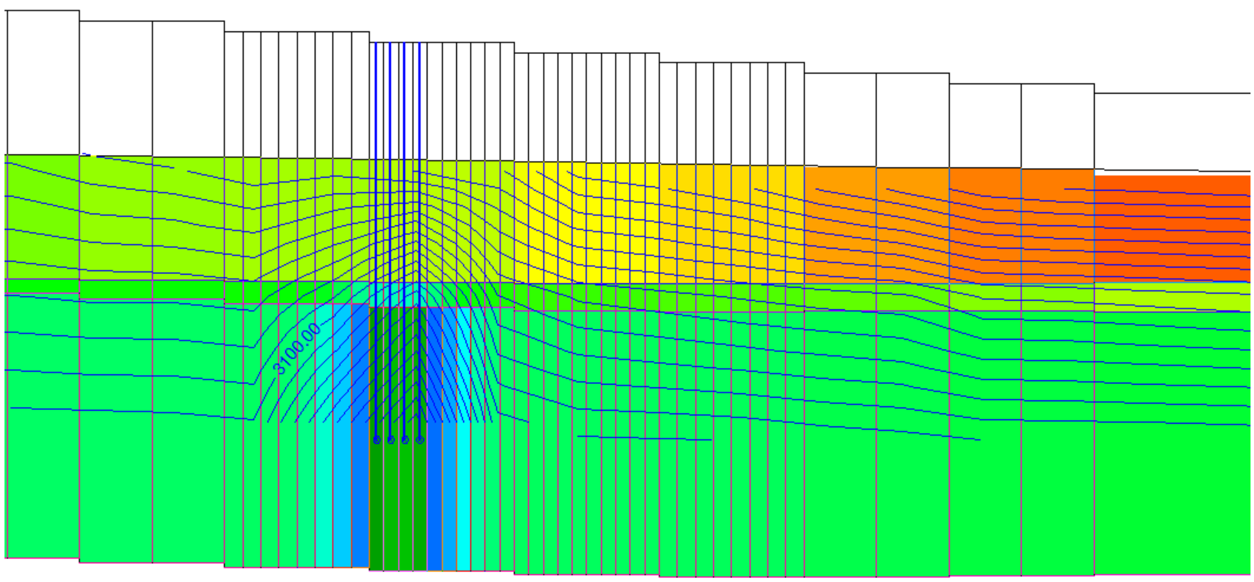
Cross-Section along Row 32



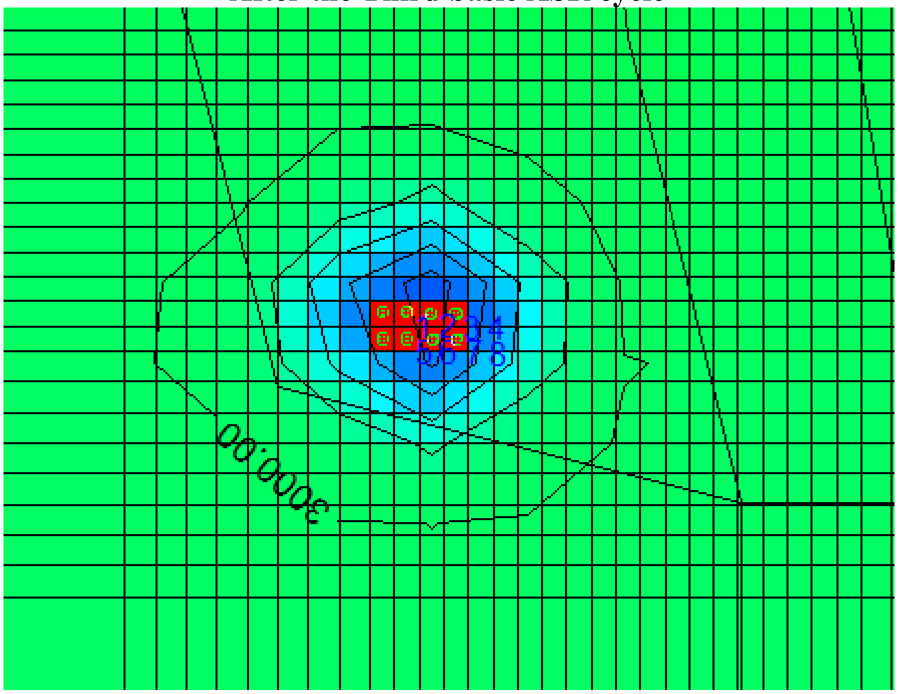
After the second basic ASR cycle



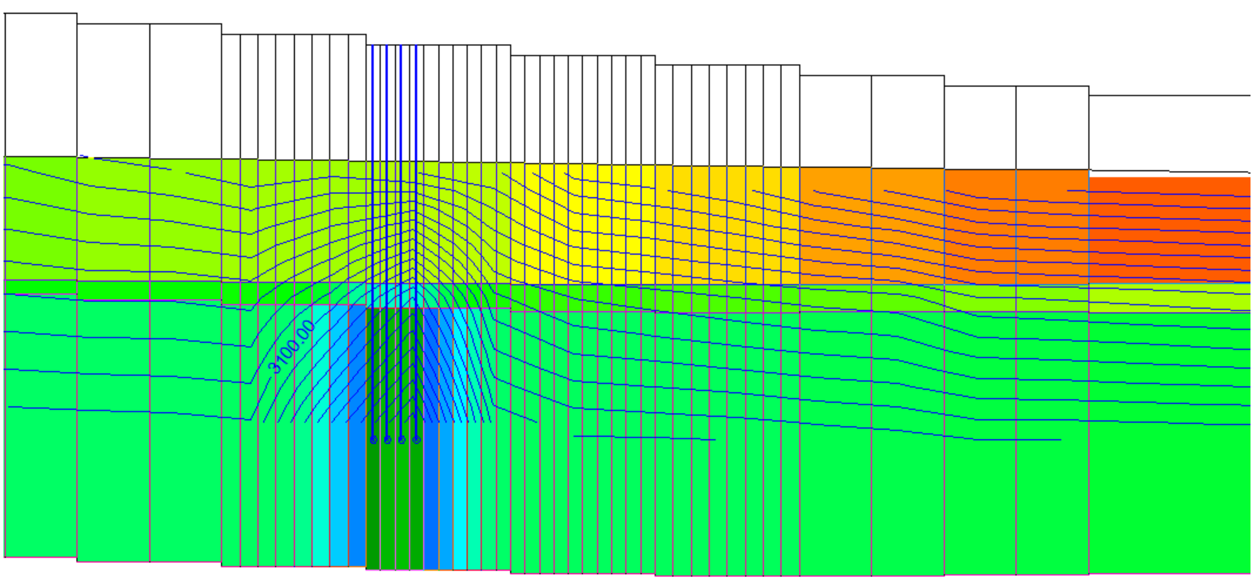
Cross-Section along Row 32

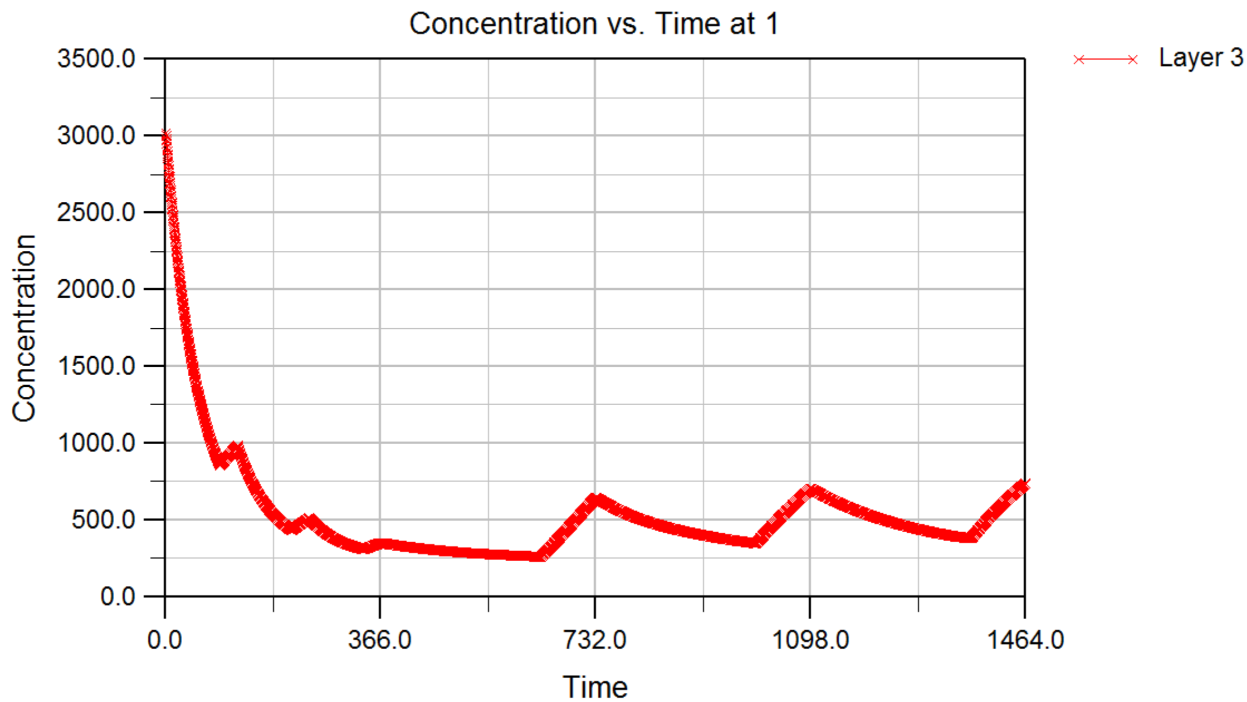


After the Third basic ASR cycle

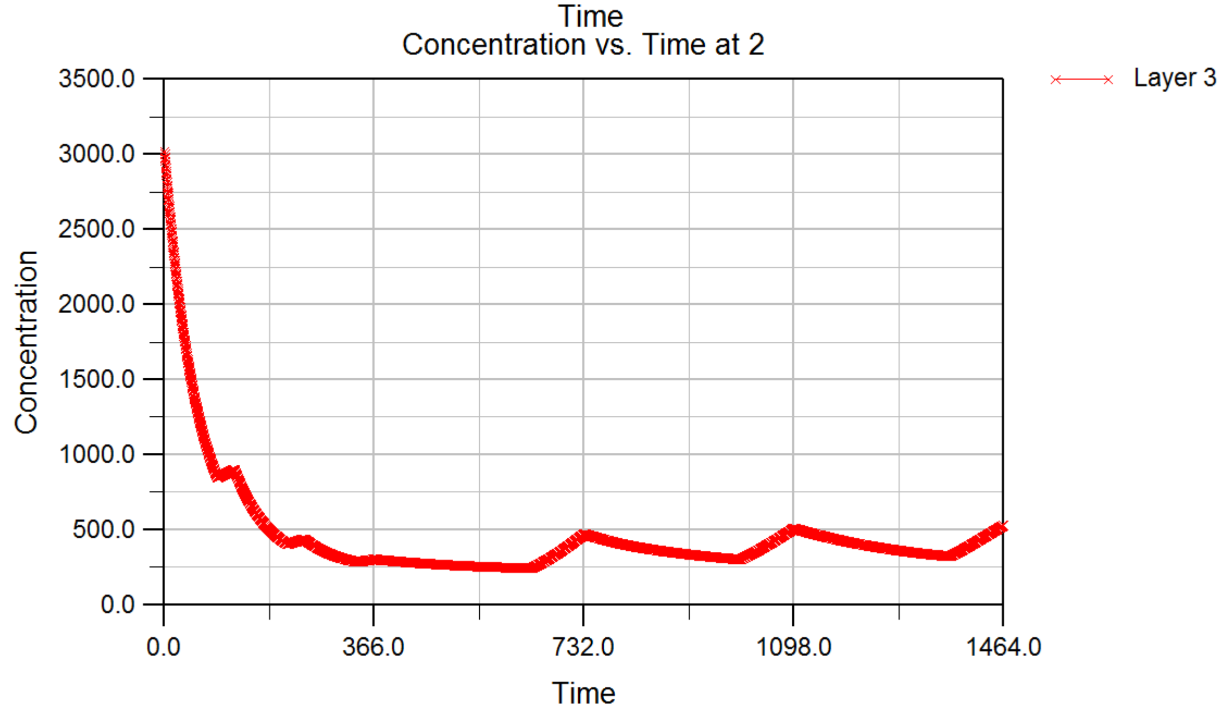


Cross-Section along Row 32

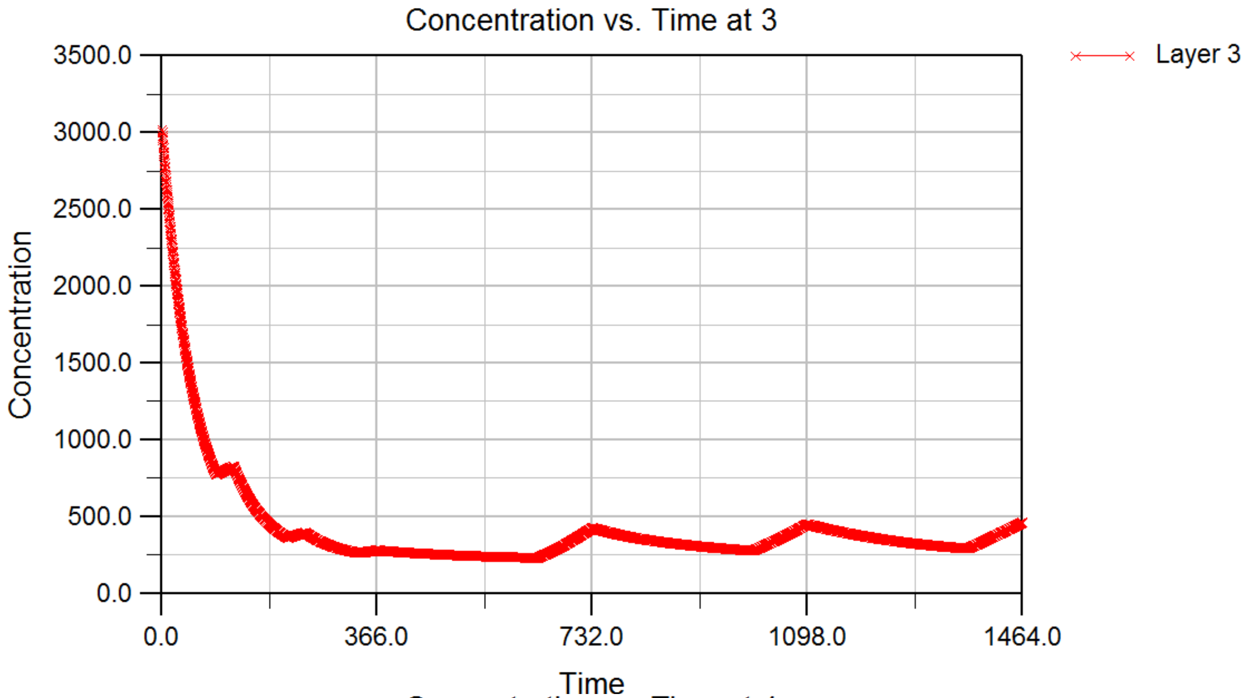


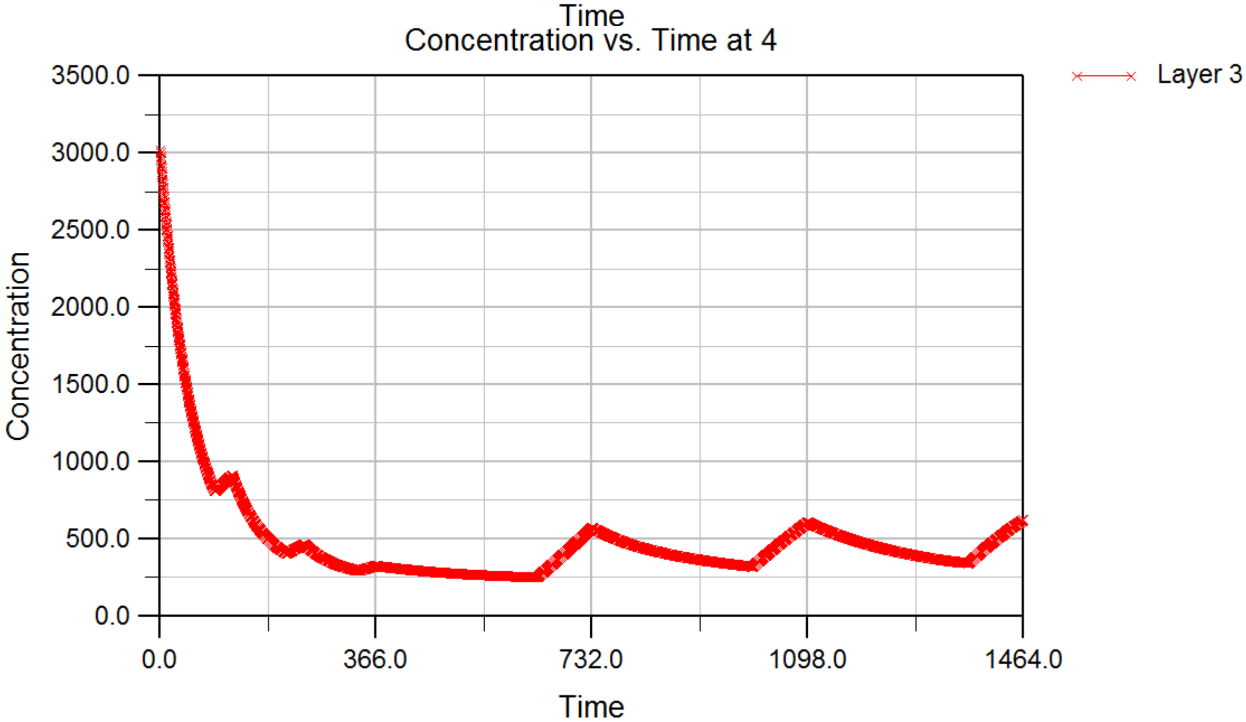


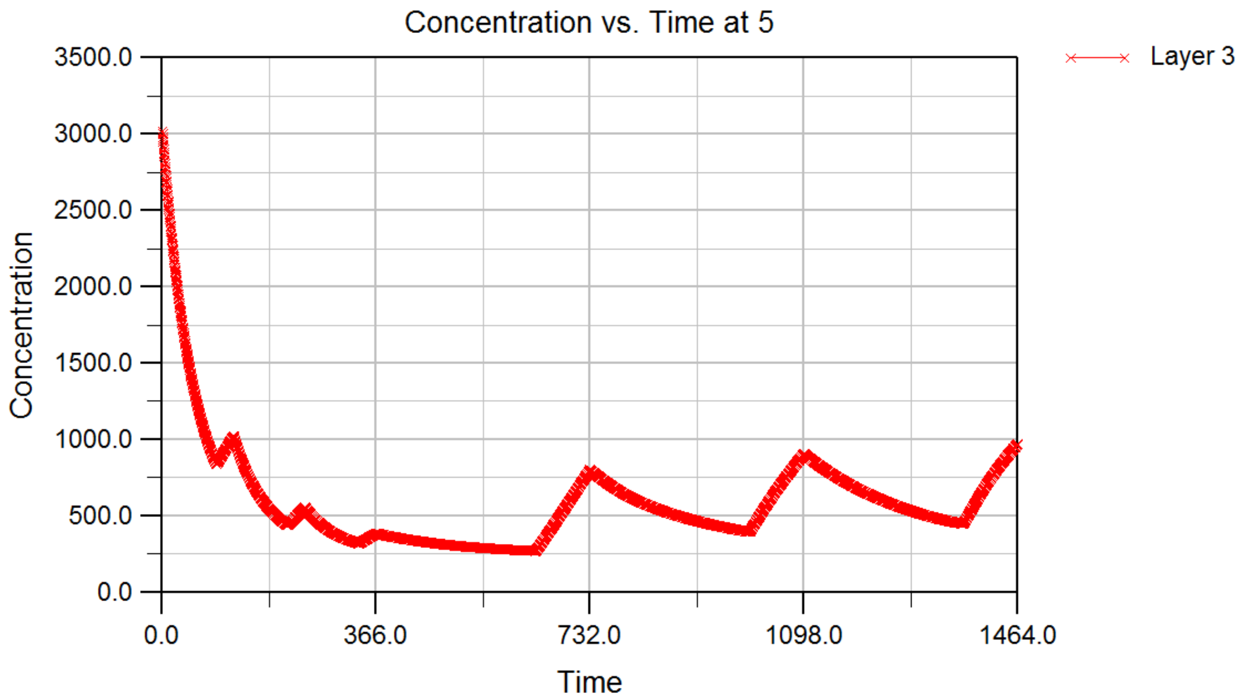
Concentration vs. Time at 1
Layer 3
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
Concentration
0.0
366.0
732.0
1098.0
1464.0
Time

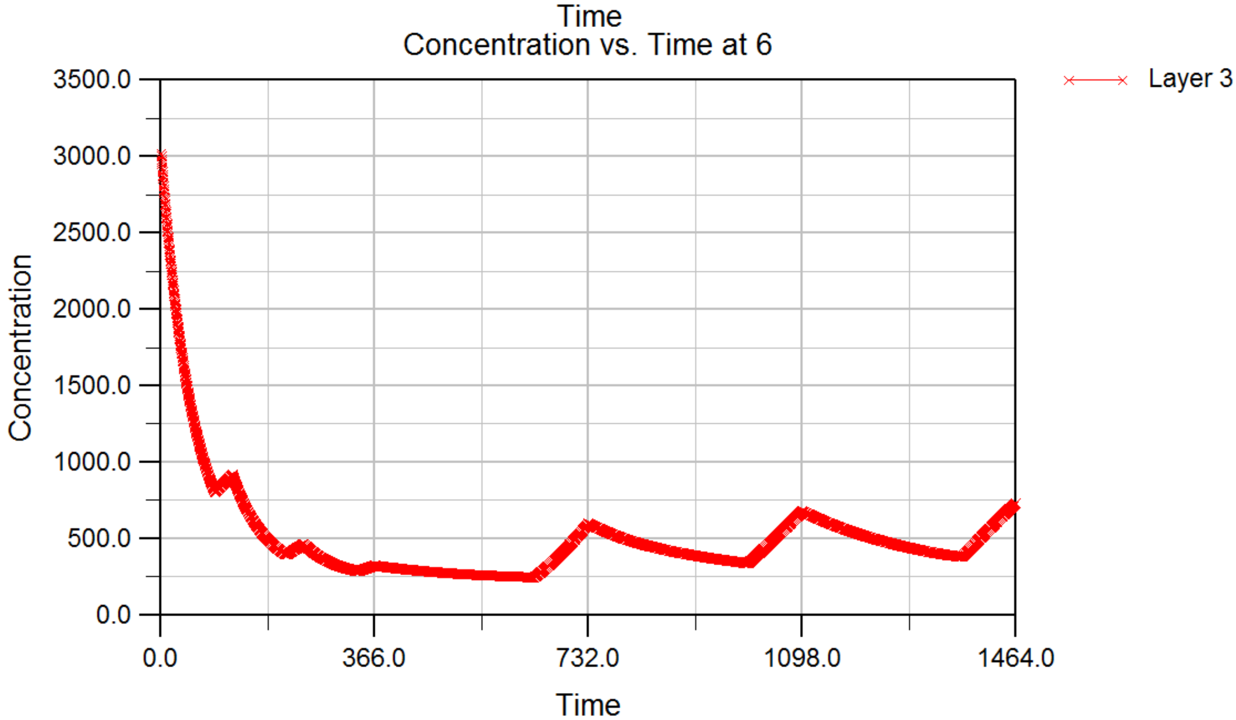


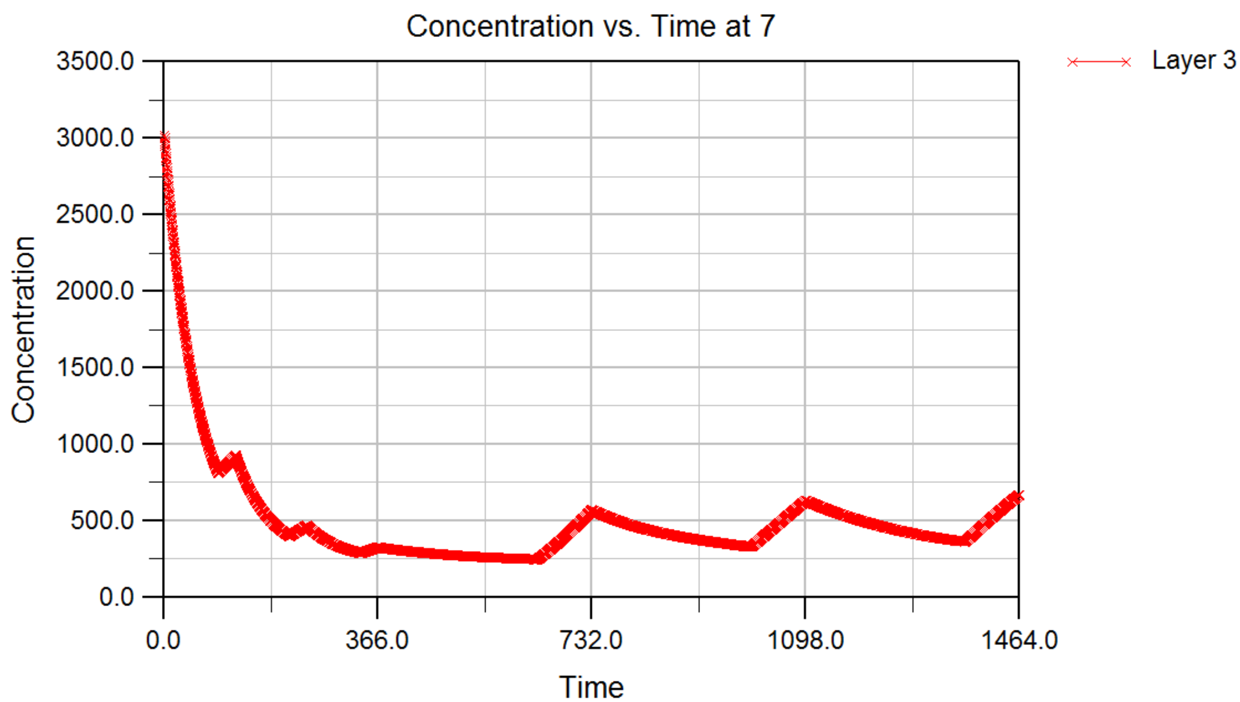
Concentration vs. Time at 2
Layer 3
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
Concentration
0.0
366.0
732.0
1098.0
1464.0
Time

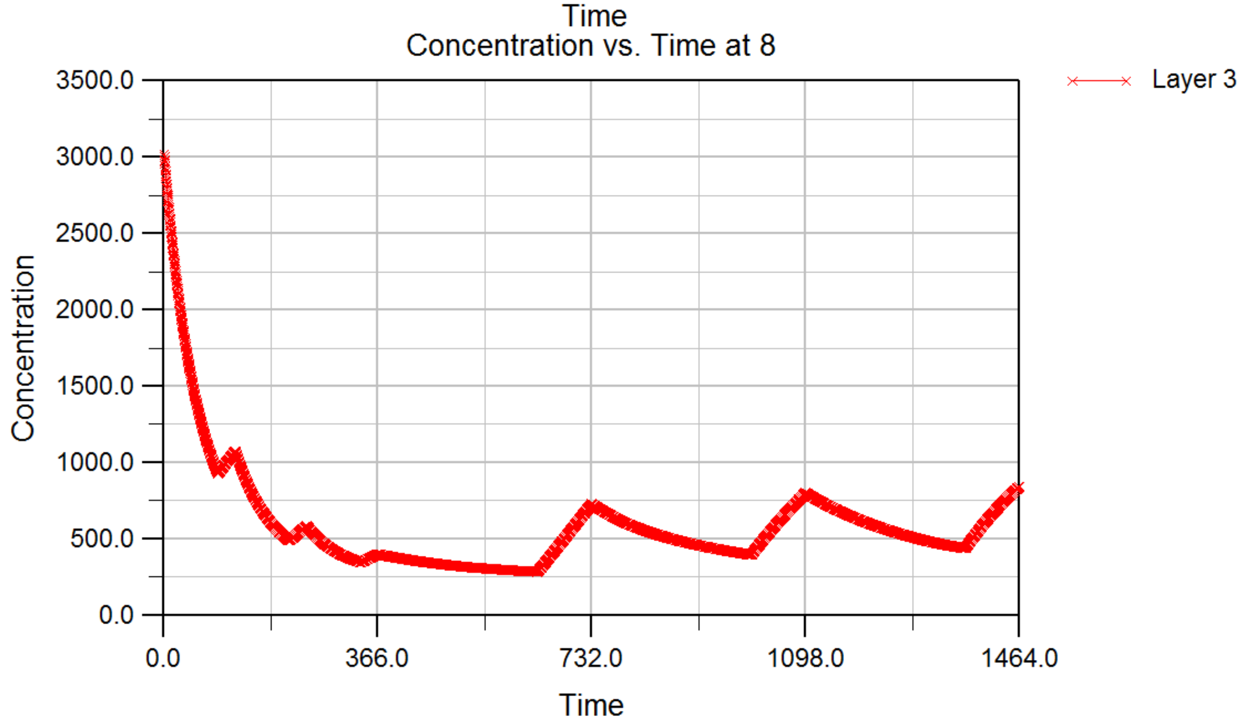

Concentration vs. Time at 3
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time


Concentration vs. Time at 4
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time

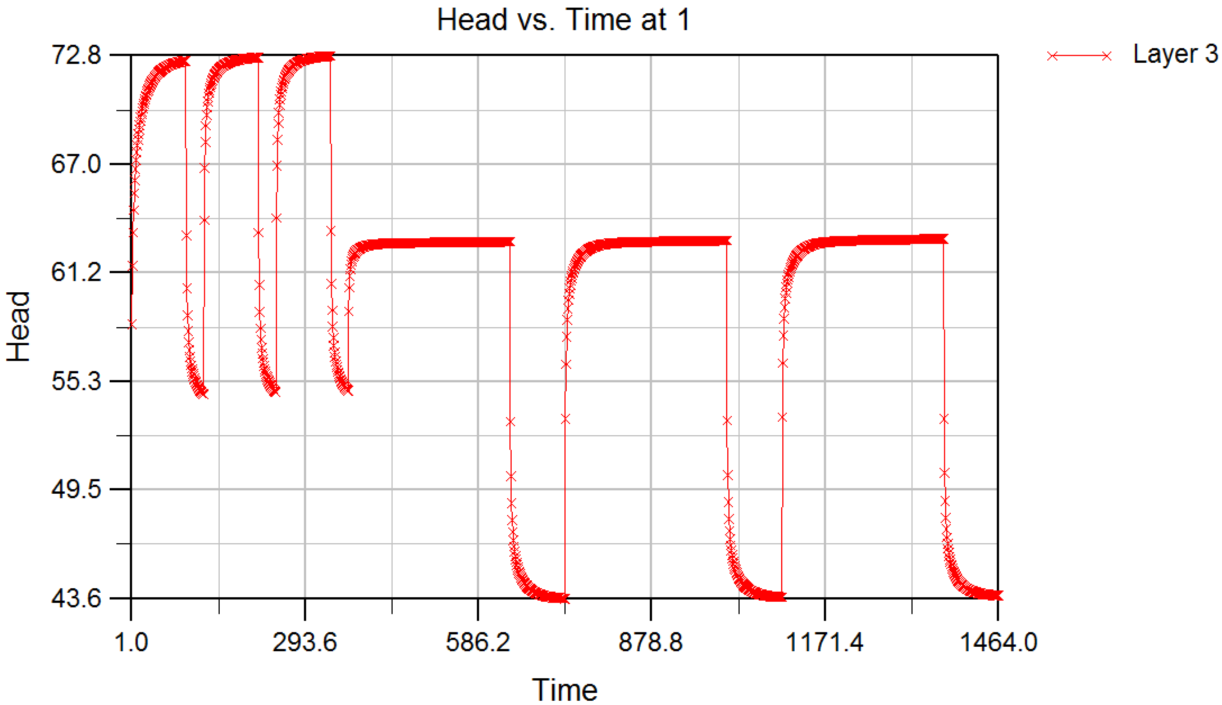

Concentration vs. Time at 5
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time

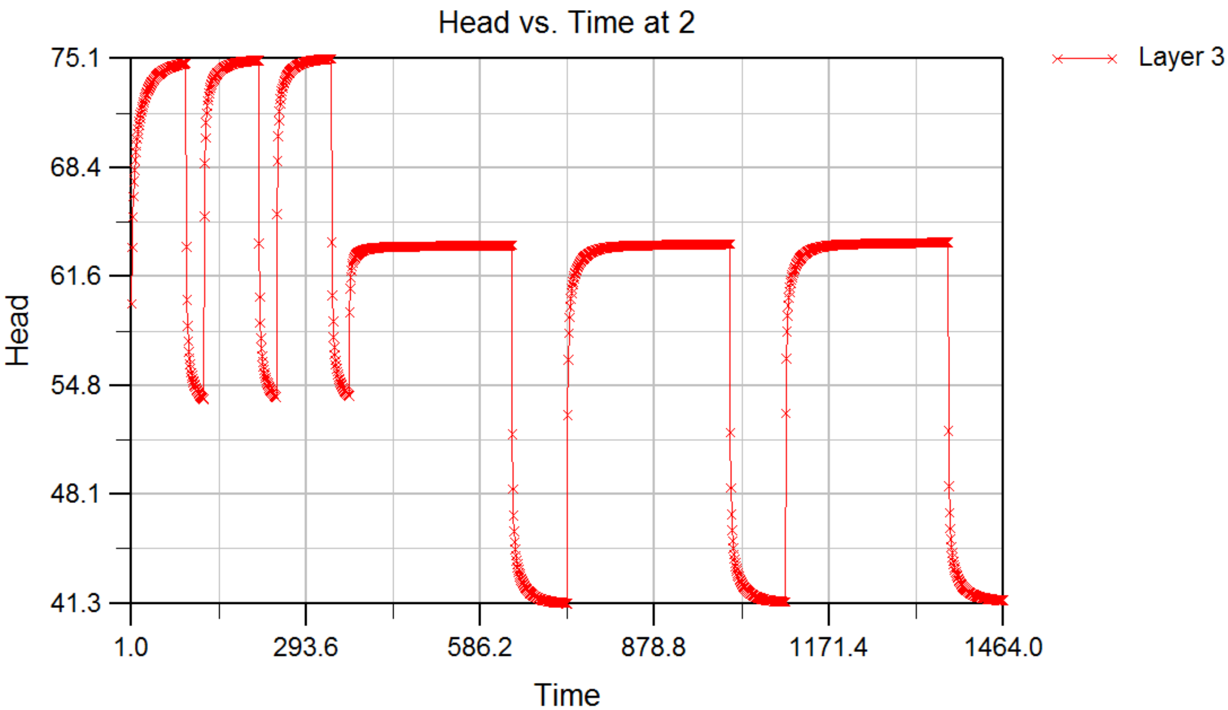

Concentration vs. Time at 6
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time

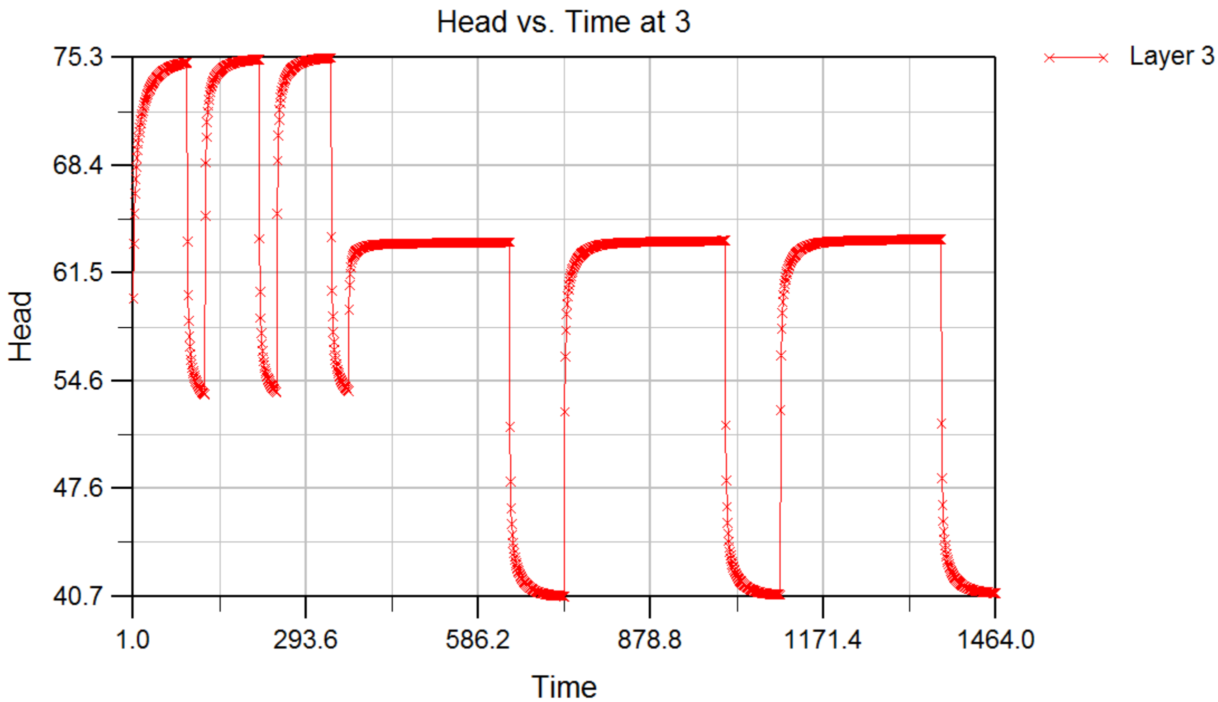

Concentration vs. Time at 7
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time

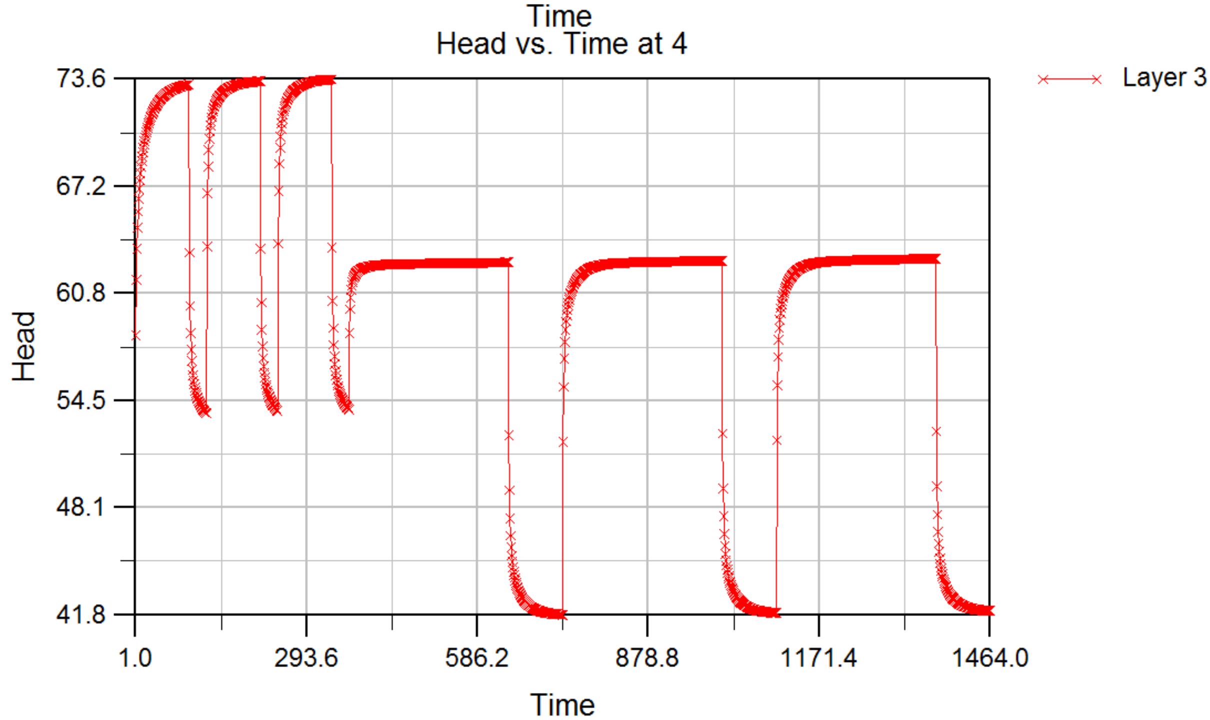

Concentration vs. Time at 8
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time

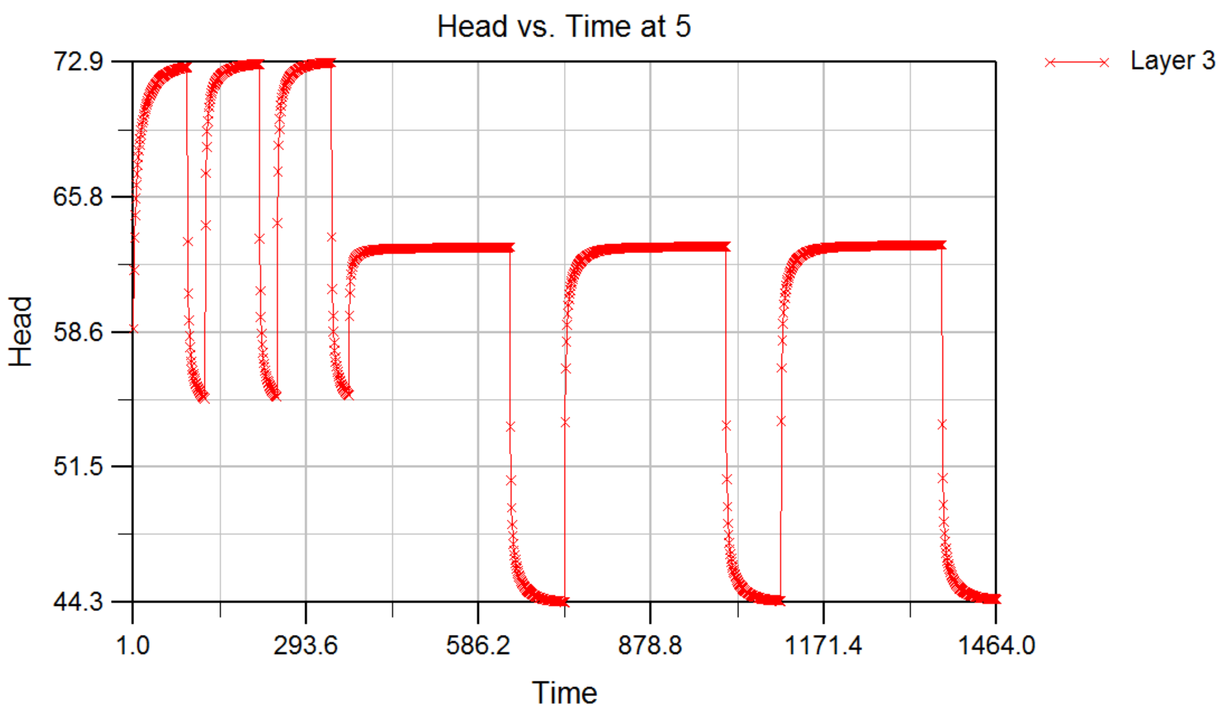
RUN 8 MODFLOW

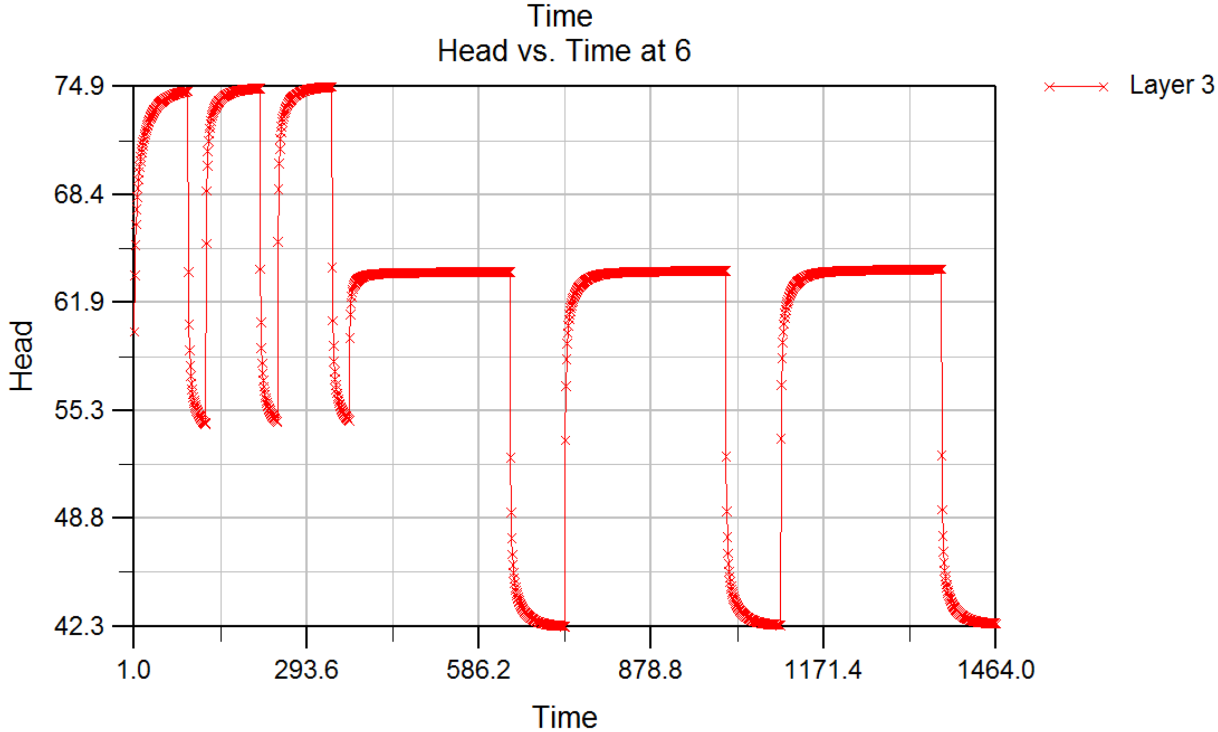


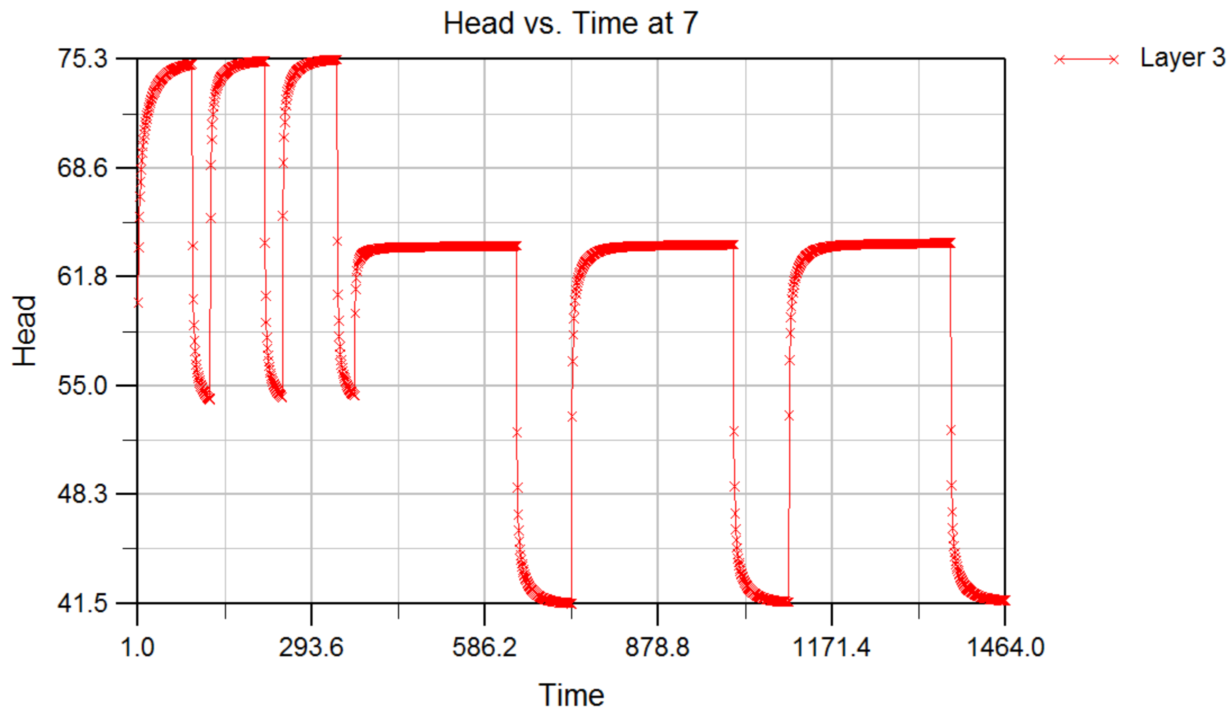


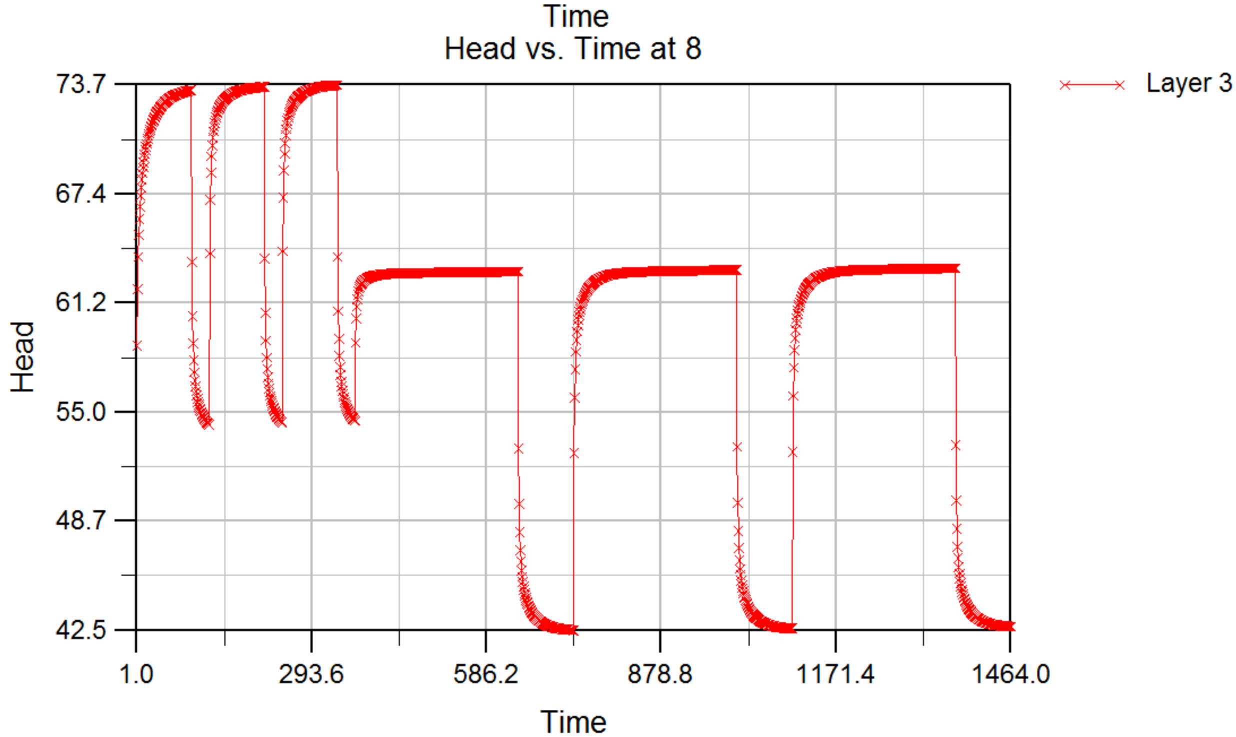

Head vs. Time at 3
Layer 3
75.3
68.4
61.5
54.6
47.6
40.7
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time


Head vs. Time at 4
Layer 3
73.6
67.2
60.8
54.5
48.1
41.8
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time


Head vs. Time at 5
Layer 3
72.9
65.8
58.6
51.5
44.3
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

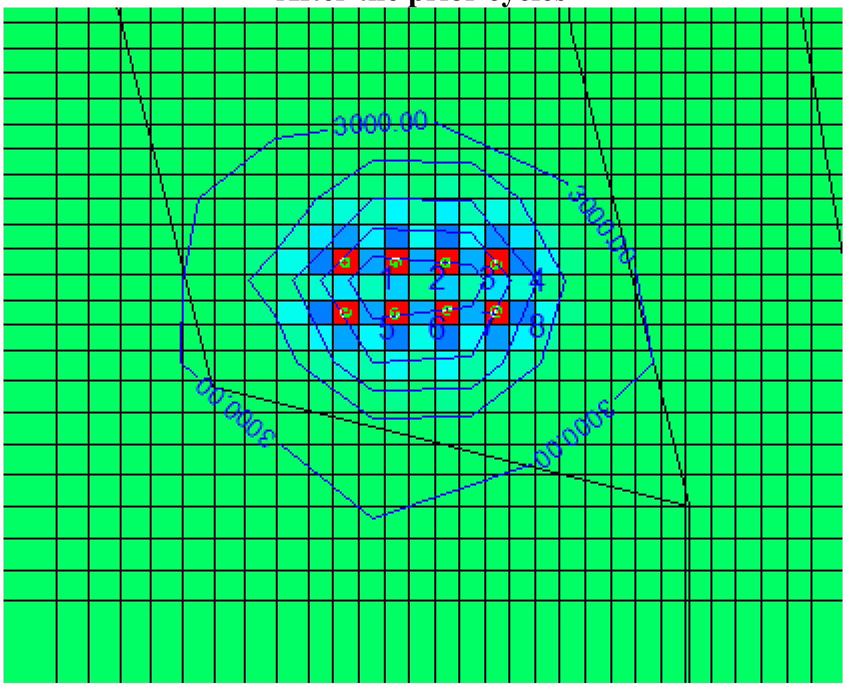

Head vs. Time at 6
Layer 3
74.9
68.4
61.9
55.3
48.8
42.3
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time


Head vs. Time at 7
Layer 3
75.3
68.6
61.8
55.0
48.3
41.5
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

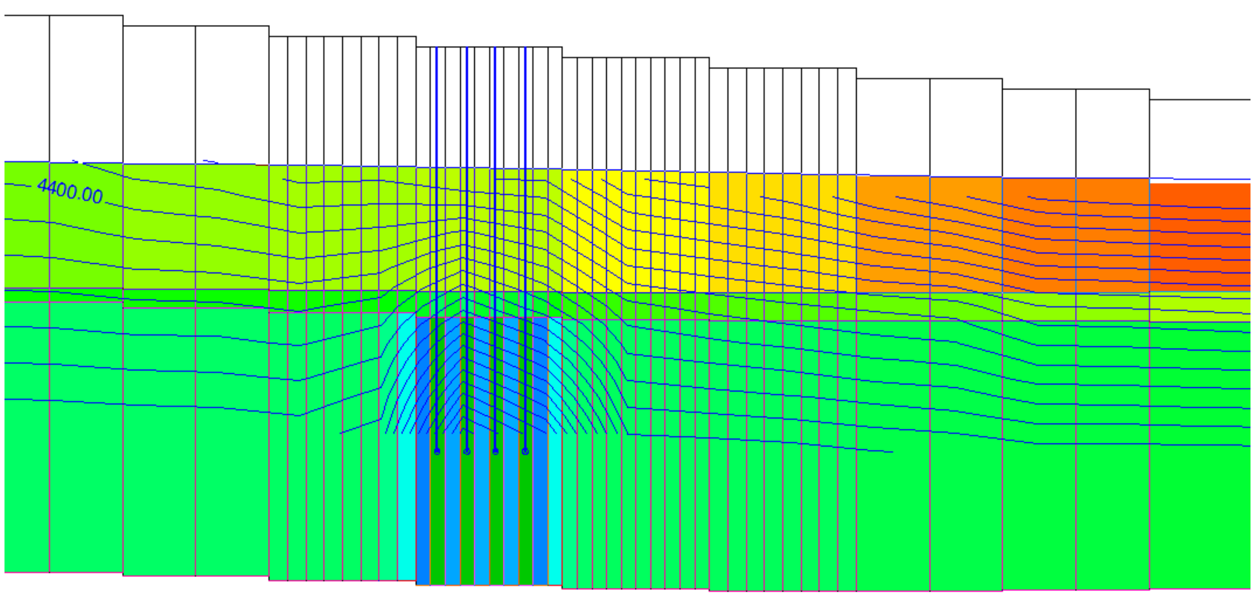

Head vs. Time at 8
Layer 3
73.7
67.4
61.2
55.0
48.7
42.5
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

RUN 8 MT3D

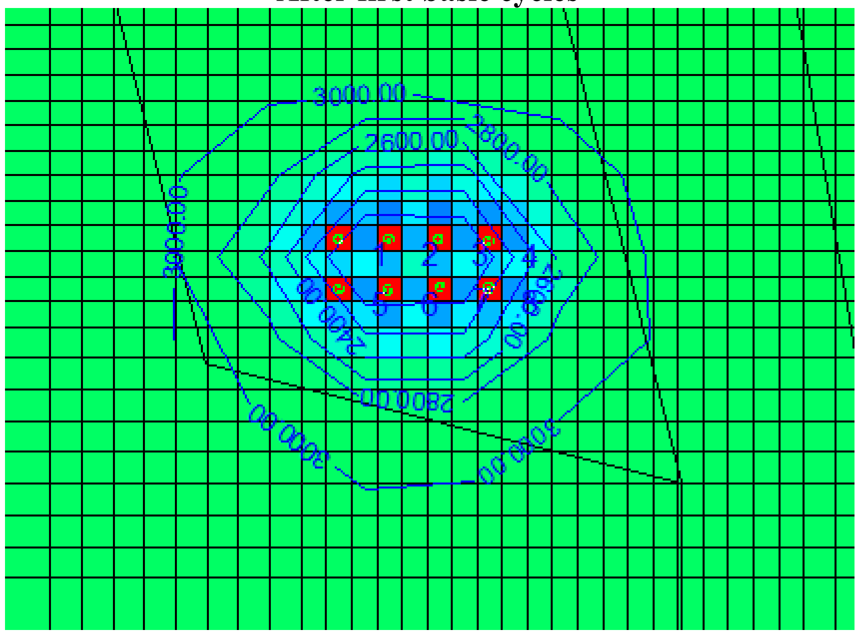
After the prior cycles



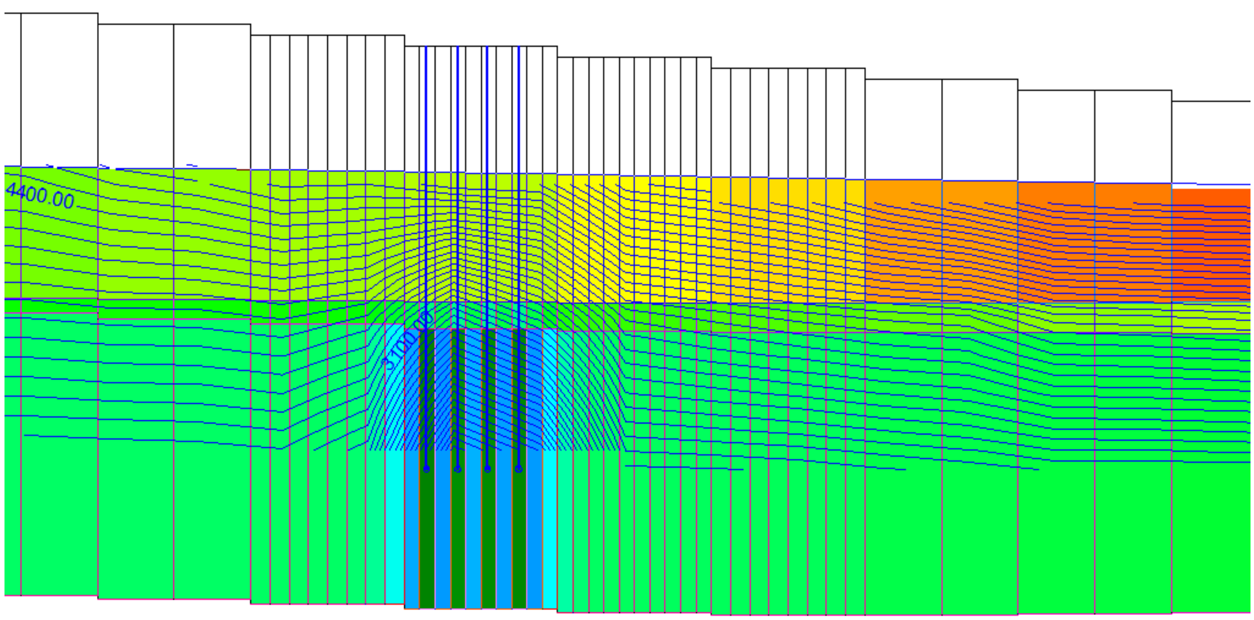
Cross-Section along Row 30



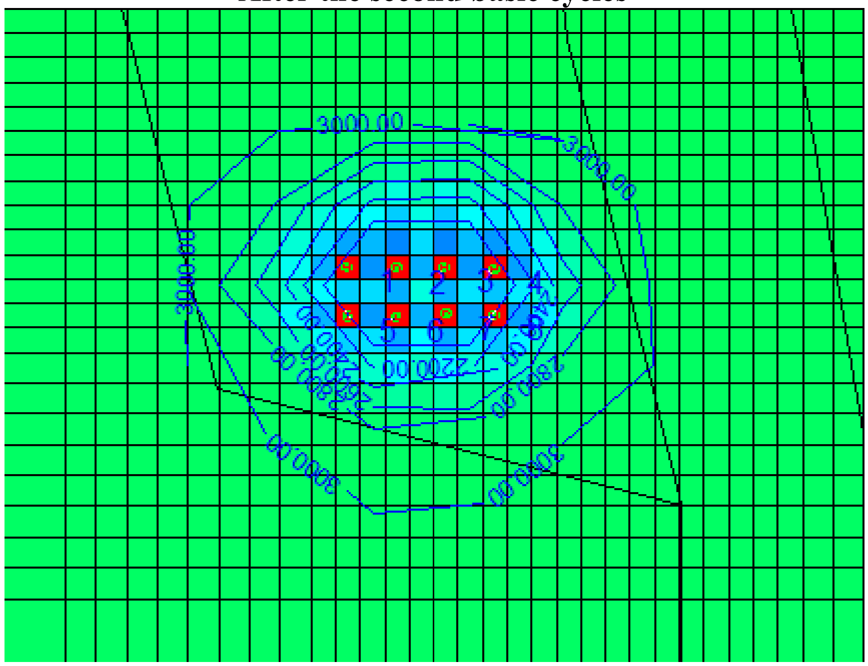
After first basic cycles



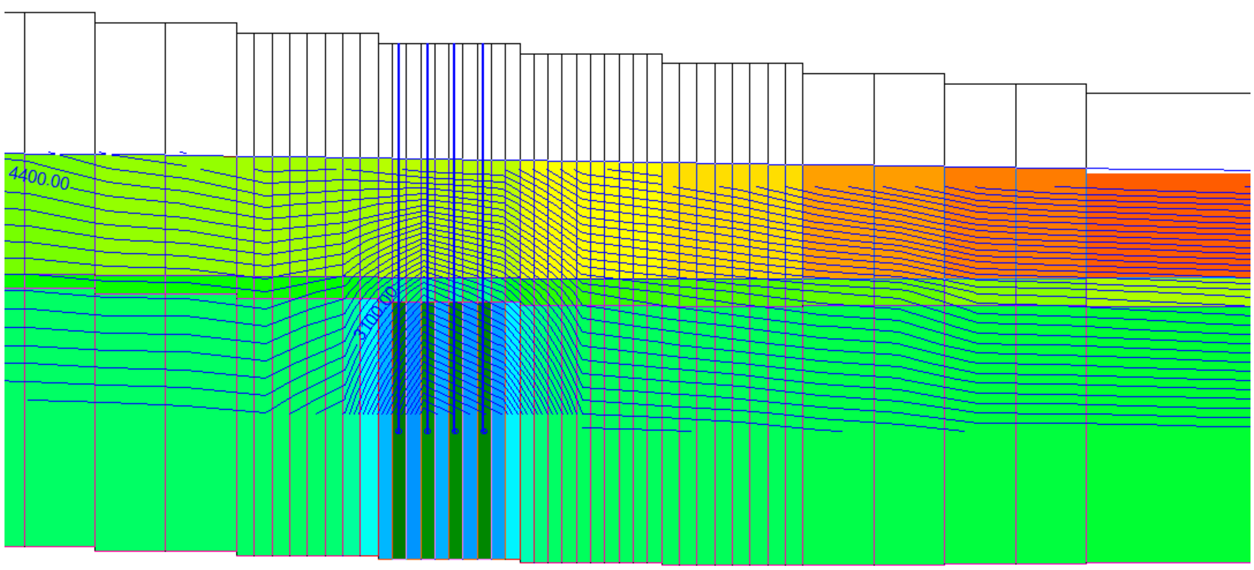
Cross-Section along Row 30



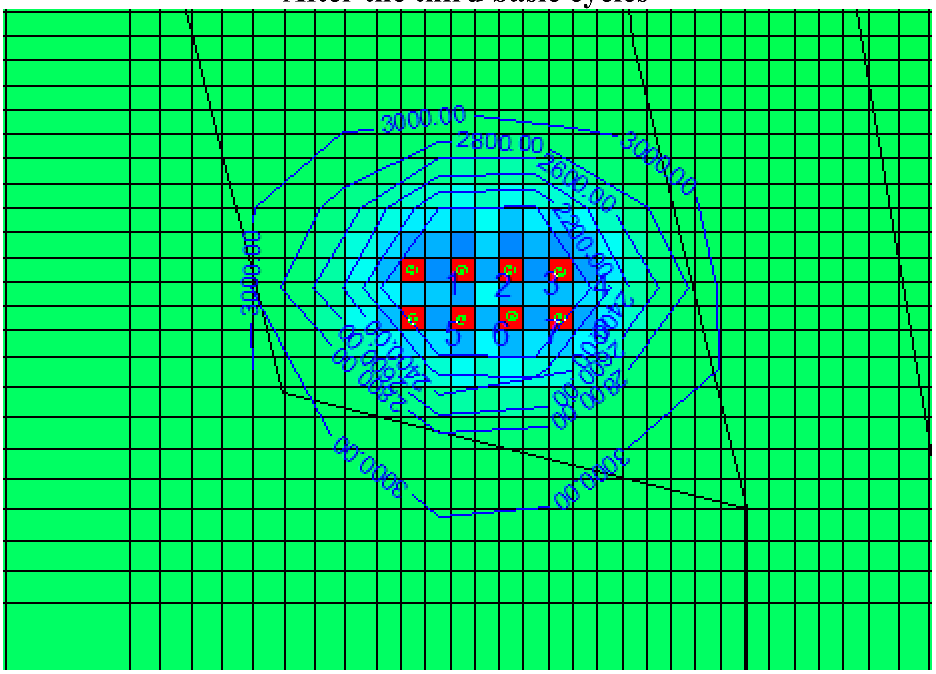
After the second basic cycles



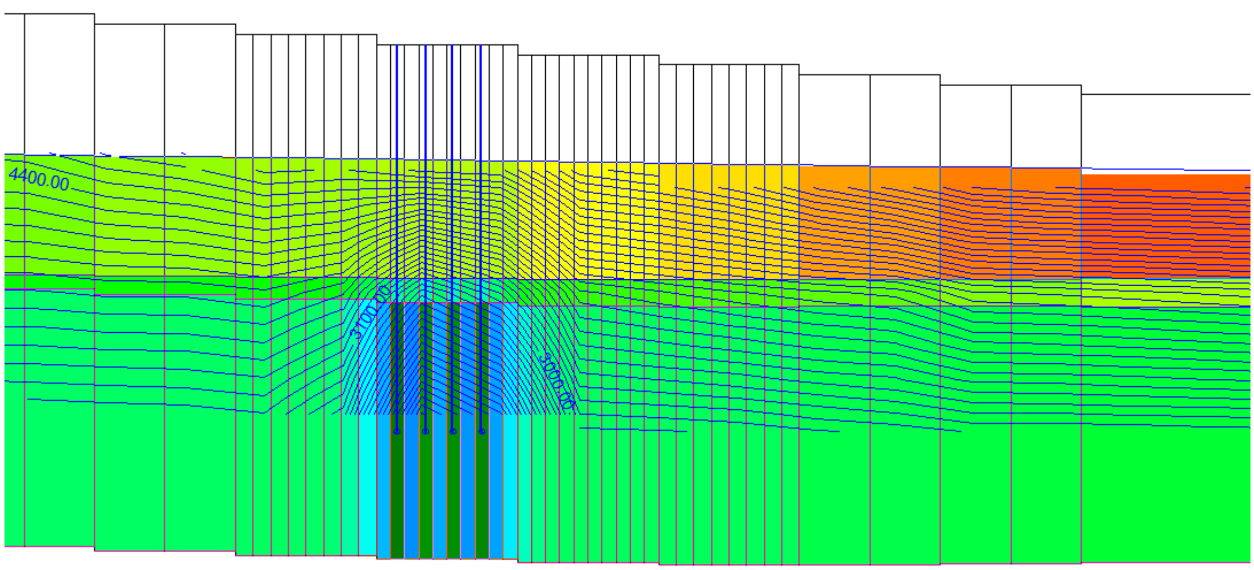
Cross-Section along Row 30

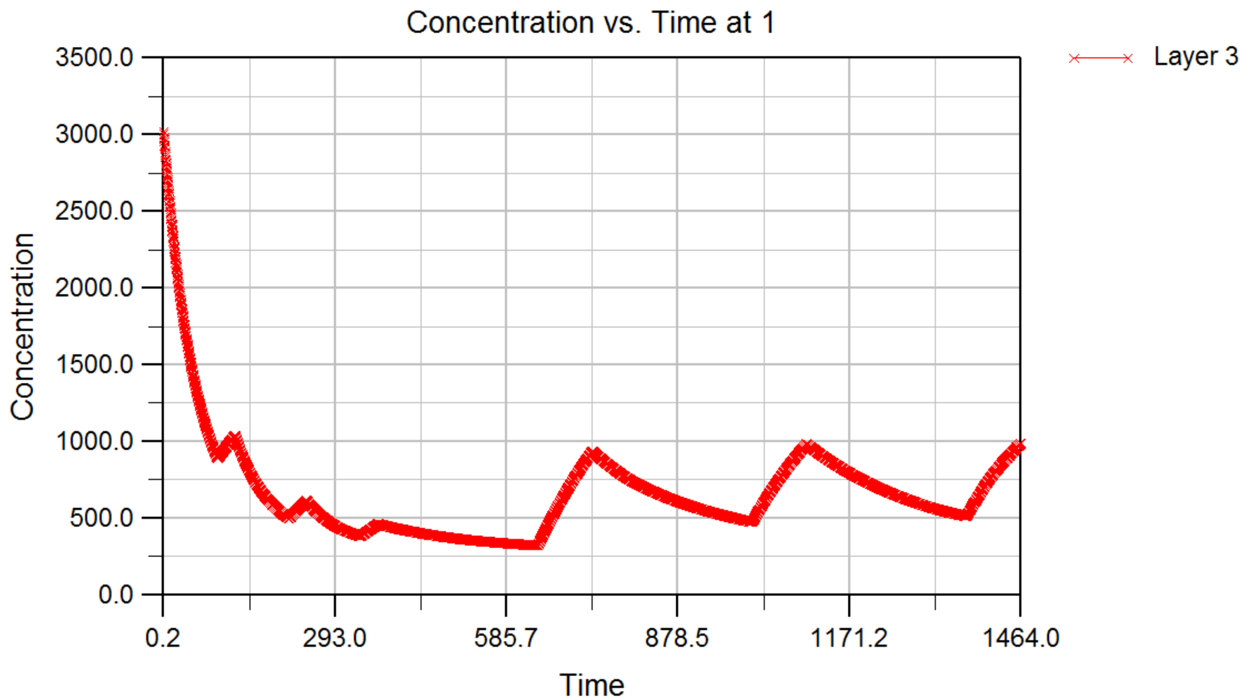


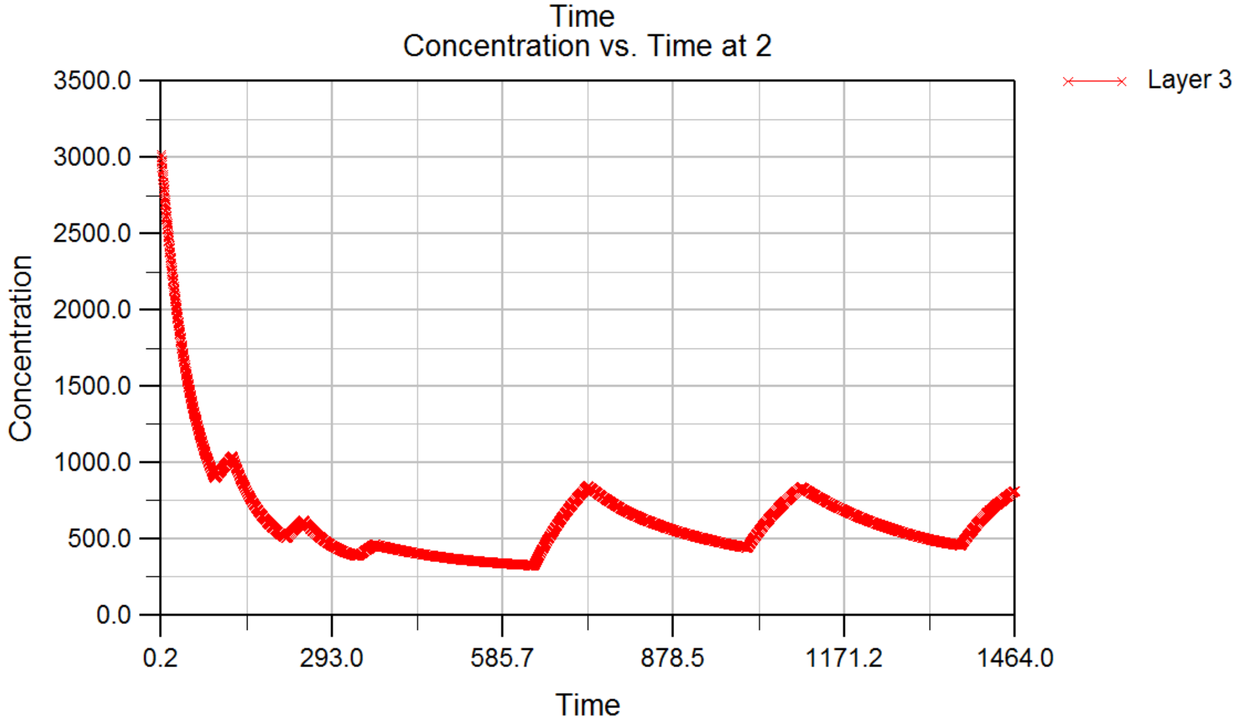
After the third basic cycles

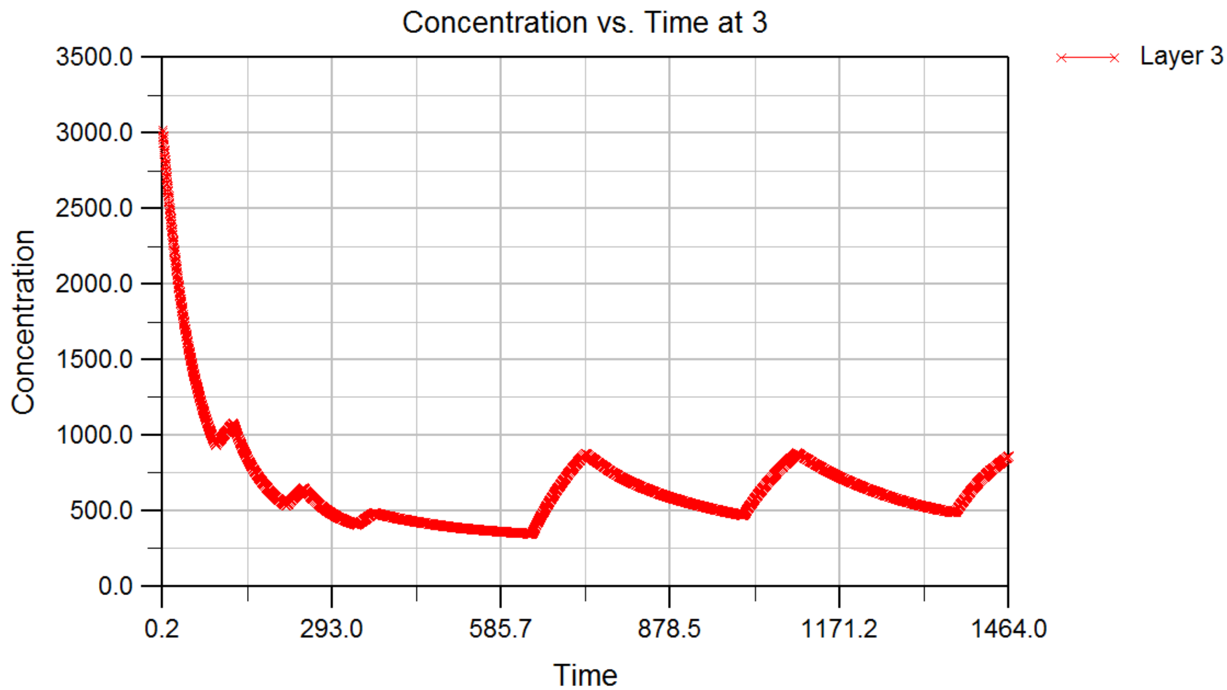


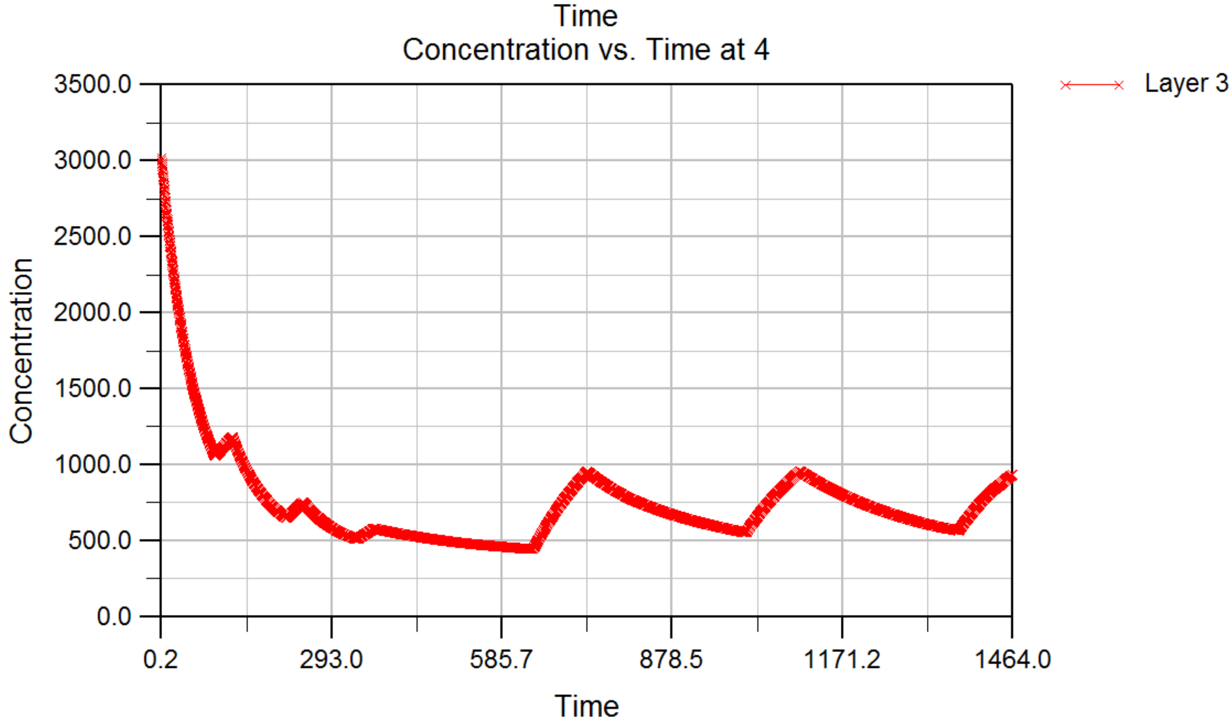
Cross-Section along Row 30

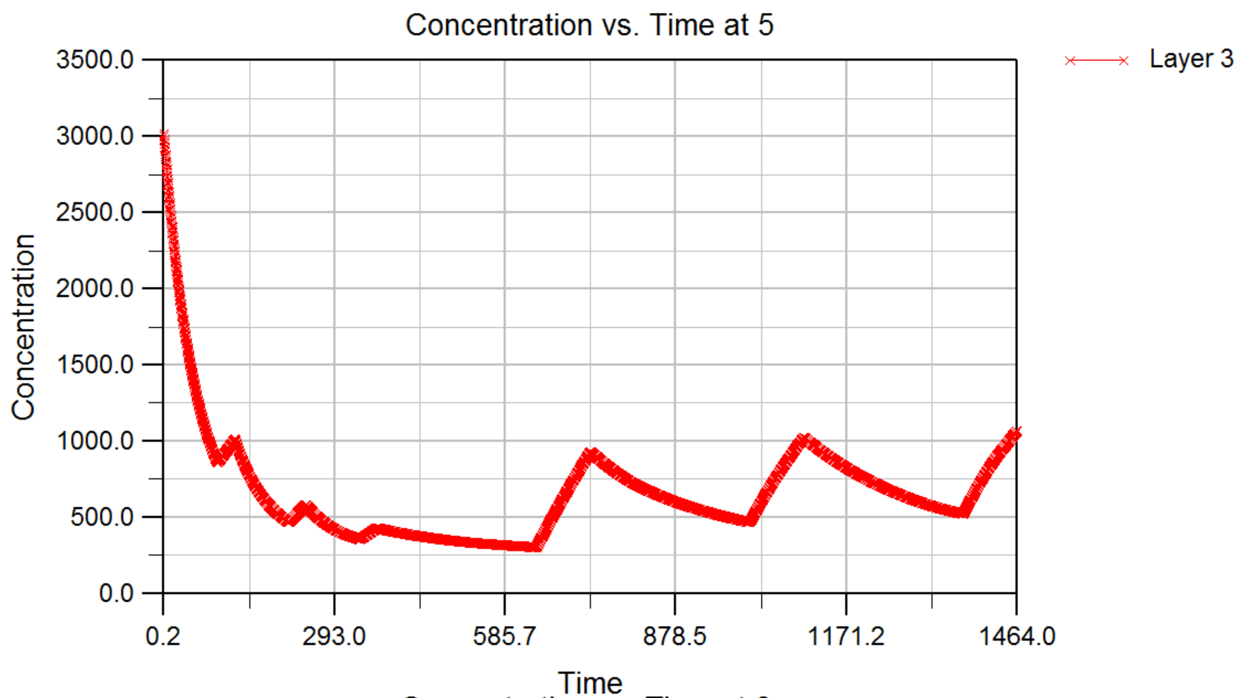


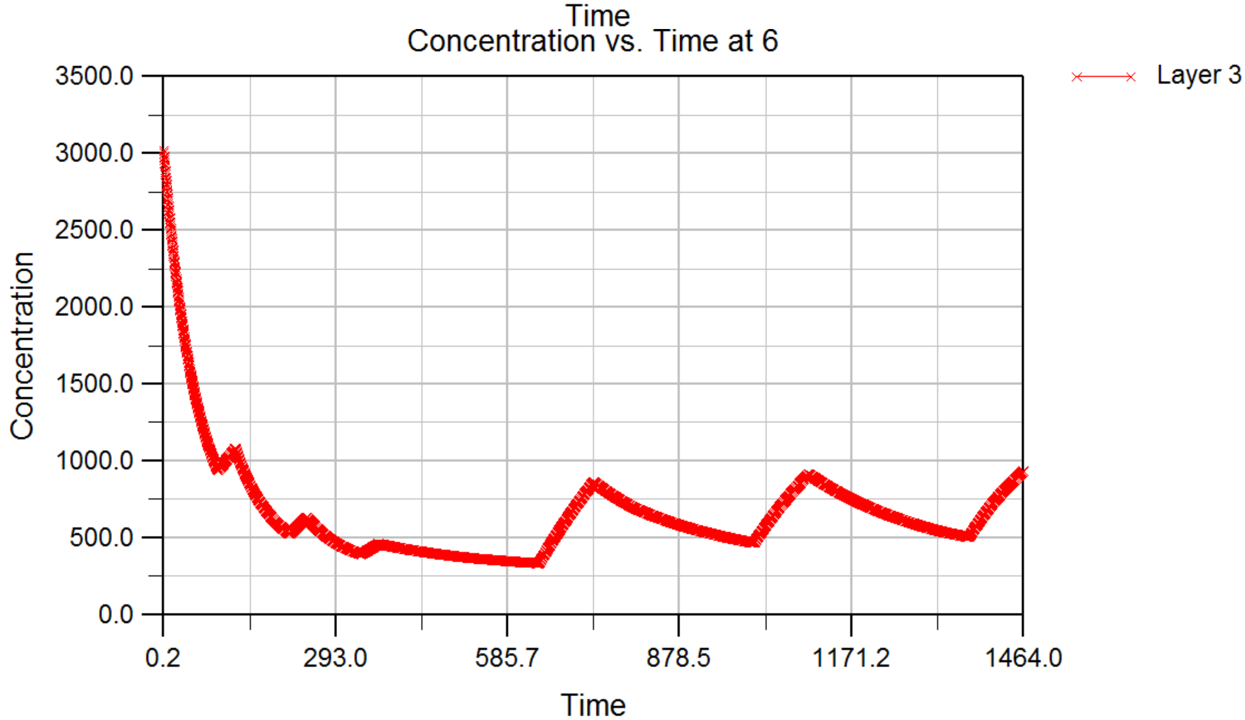

Concentration vs. Time at 1
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.2
293.0
585.7
878.5
1171.2
1464.0
Time

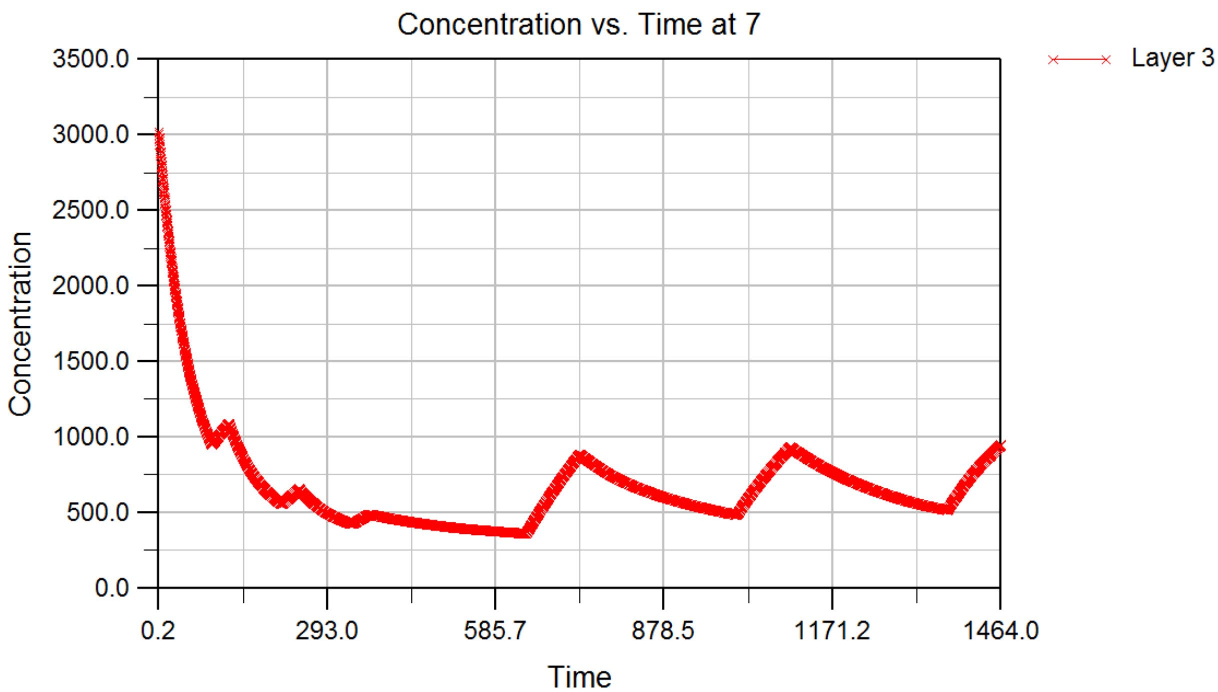

Concentration vs. Time at 2
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.2
293.0
585.7
878.5
1171.2
1464.0
Time

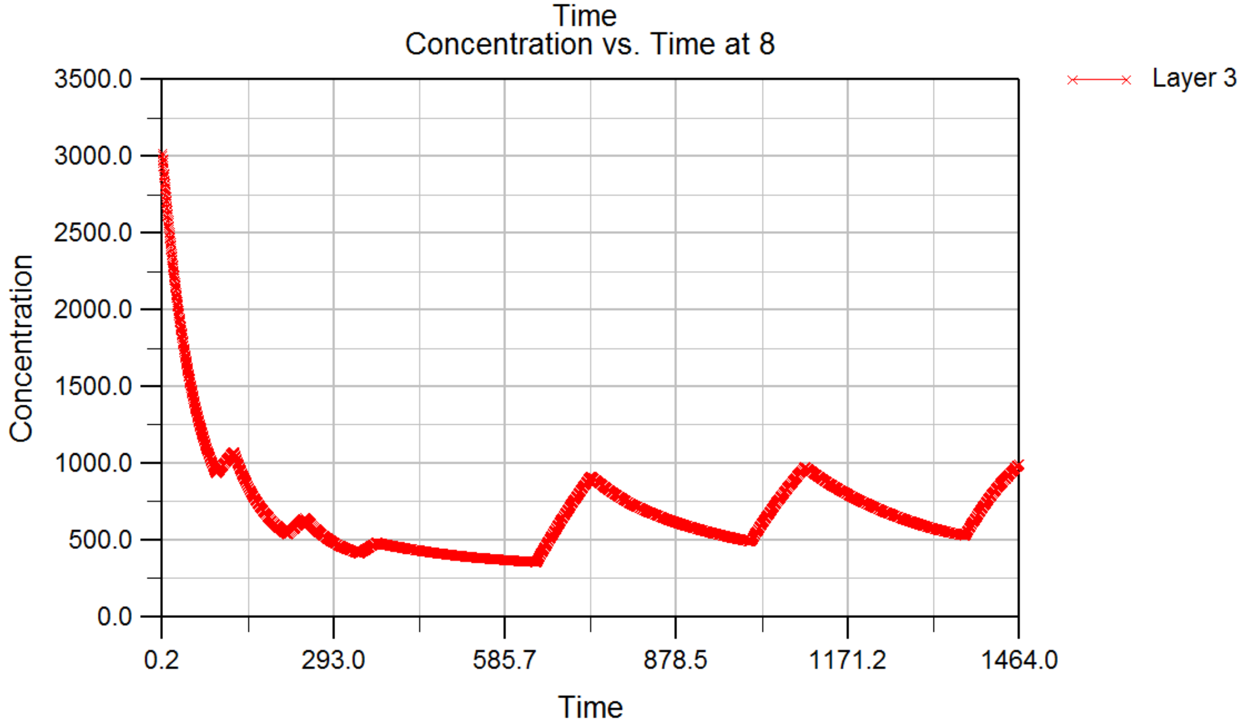

Concentration vs. Time at 3
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.2
293.0
585.7
878.5
1171.2
1464.0
Time


Concentration vs. Time at 4
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.2
293.0
585.7
878.5
1171.2
1464.0
Time

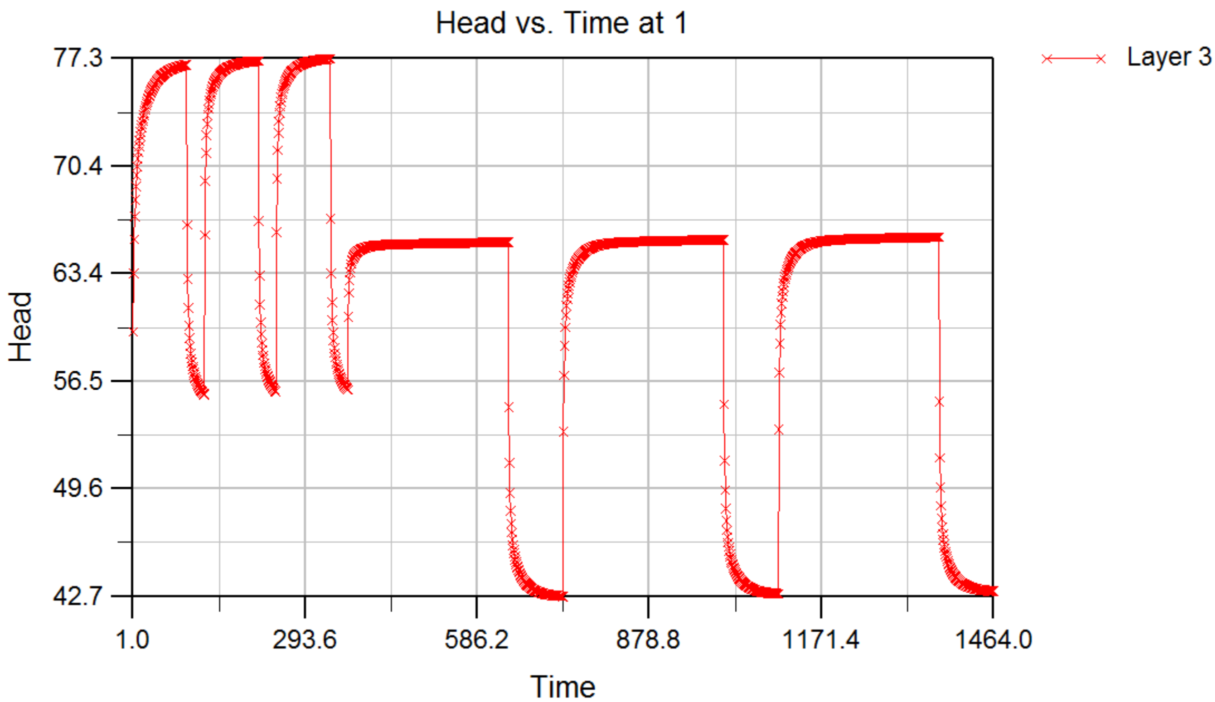

Concentration vs. Time at 5
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.2
293.0
585.7
878.5
1171.2
1464.0
Time


Concentration vs. Time at 6
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.2
293.0
585.7
878.5
1171.2
1464.0
Time

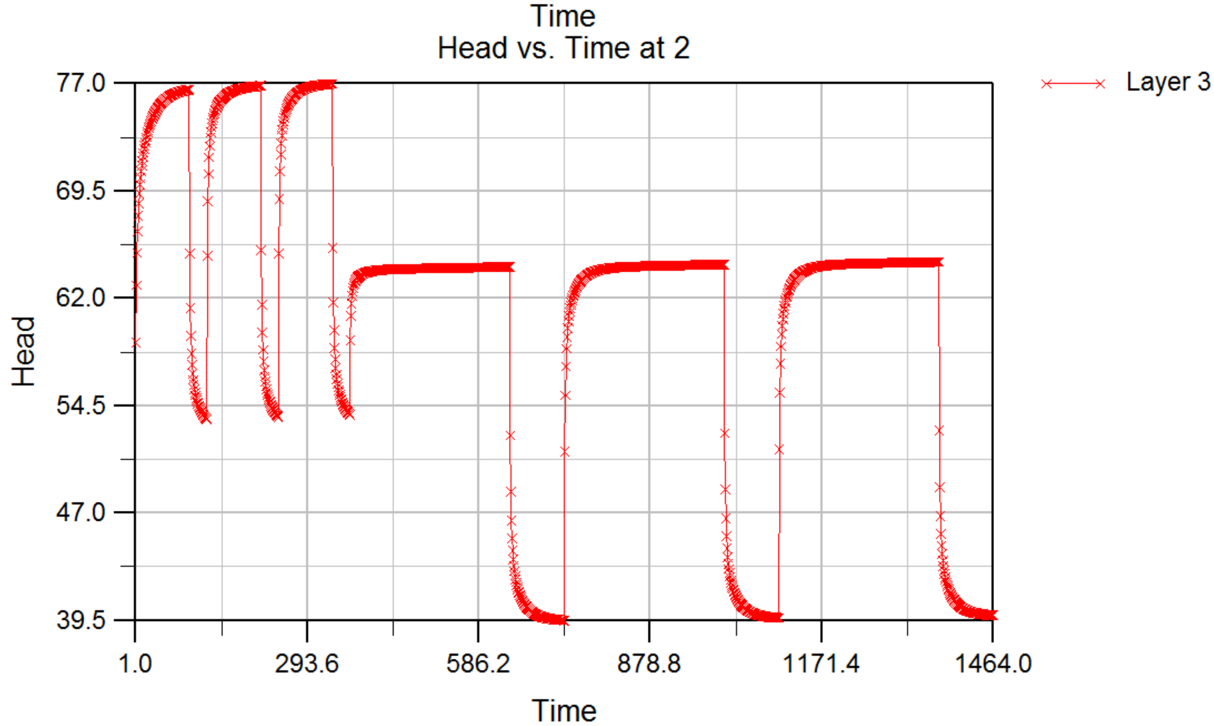

Concentration vs. Time at 7
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.2
293.0
585.7
878.5
1171.2
1464.0
Time


Concentration vs. Time at 8
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.2
293.0
585.7
878.5
1171.2
1464.0
Time

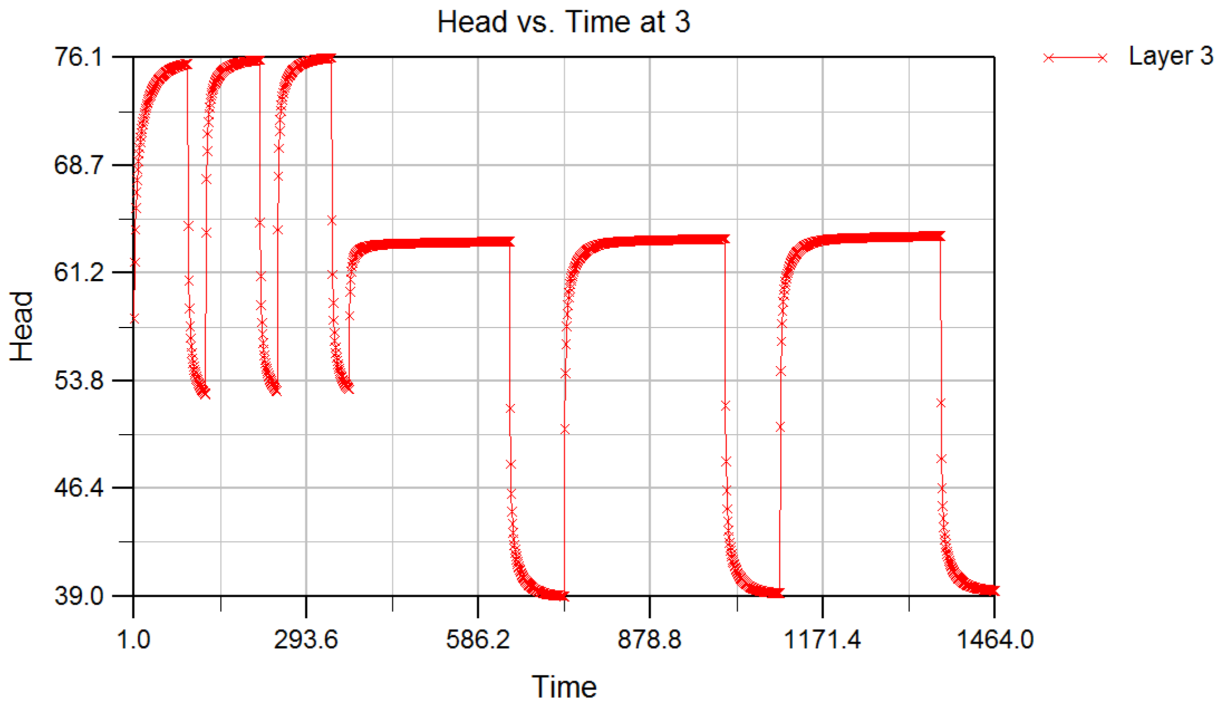
Run 9

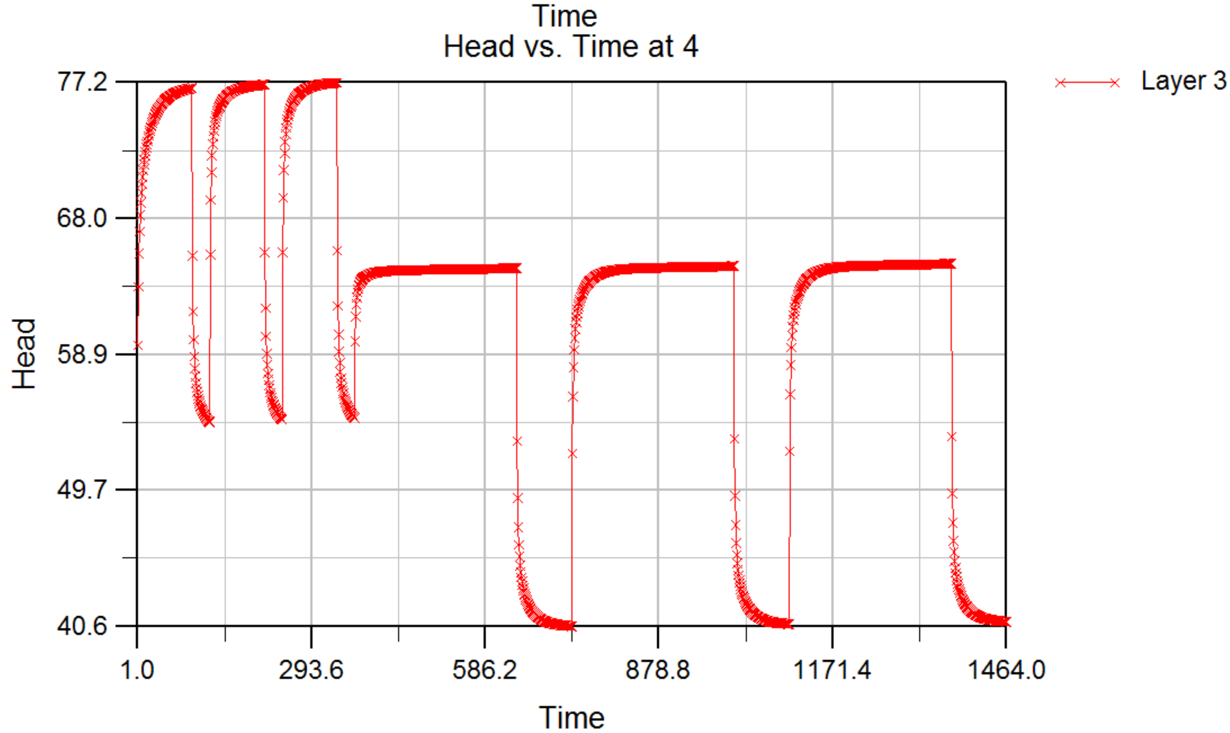


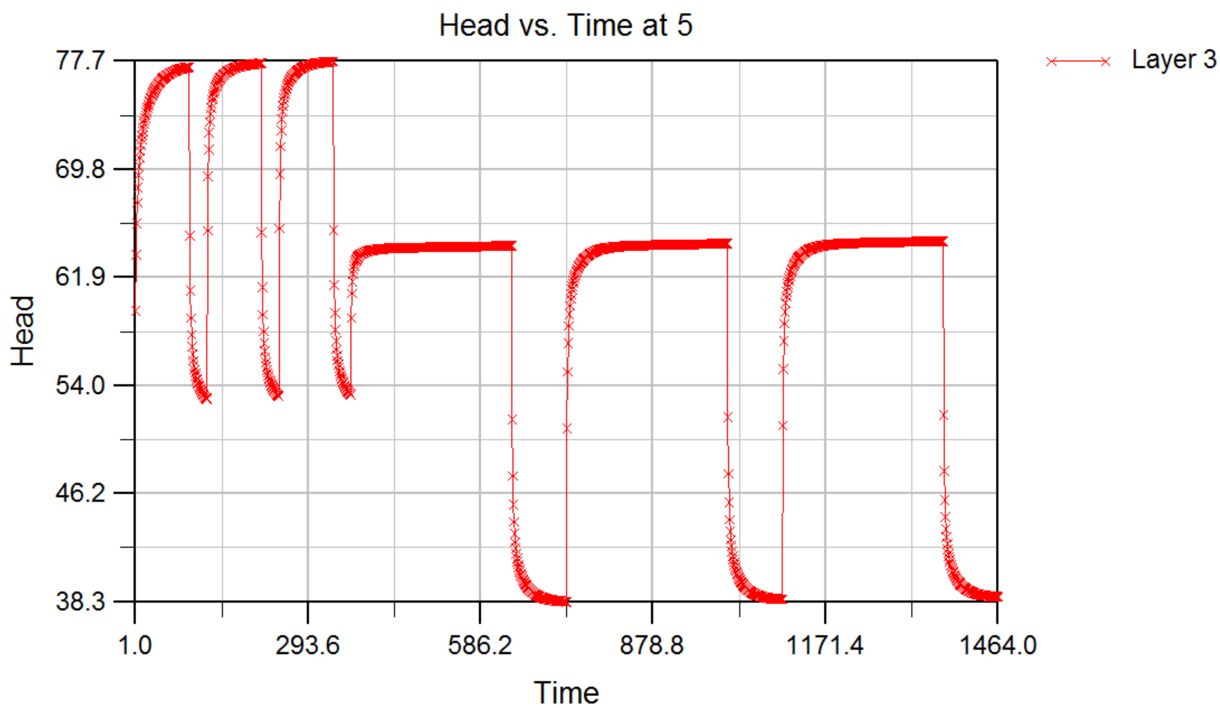
Head vs. Time at 1
Layer 3
77.3
70.4
63.4
56.5
49.6
42.7
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time



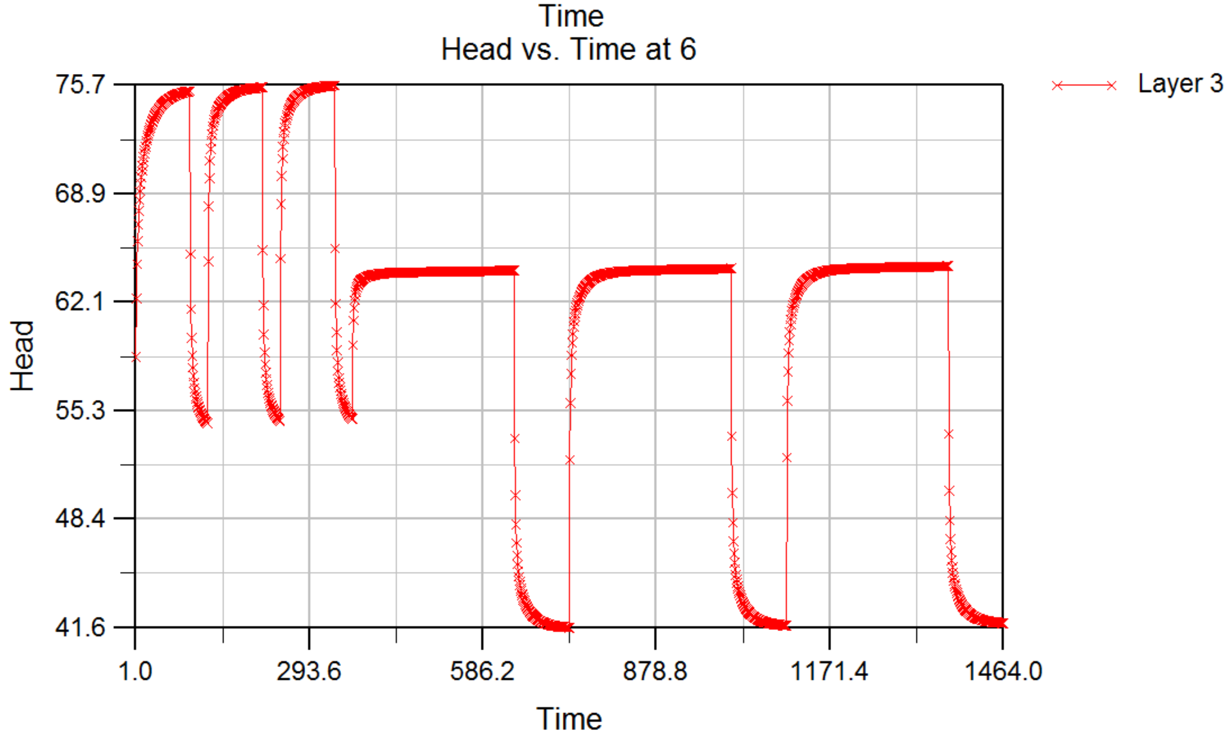
Head vs. Time at 2
Layer 3
77.0
69.5
62.0
54.5
47.0
39.5
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time


Head vs. Time at 3
Layer 3
76.1
68.7
61.2
53.8
46.4
39.0
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

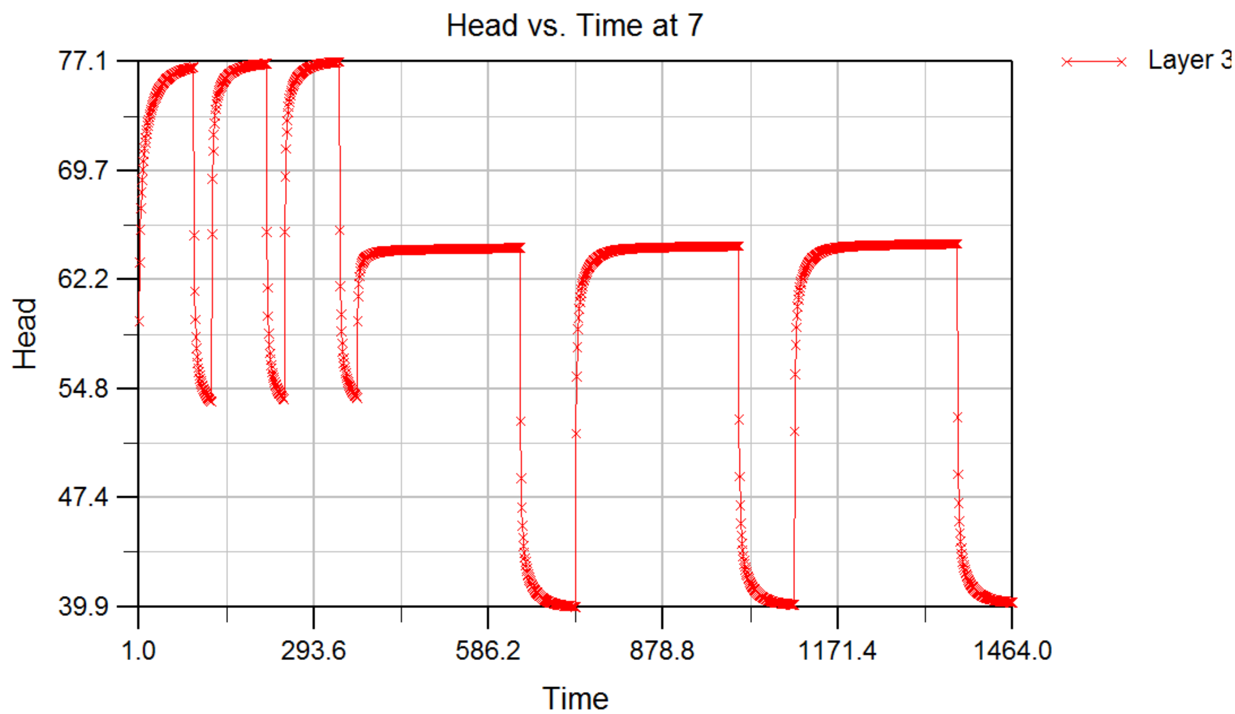

Head vs. Time at 4
Layer 3
77.2
68.0
58.9
49.7
40.6
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

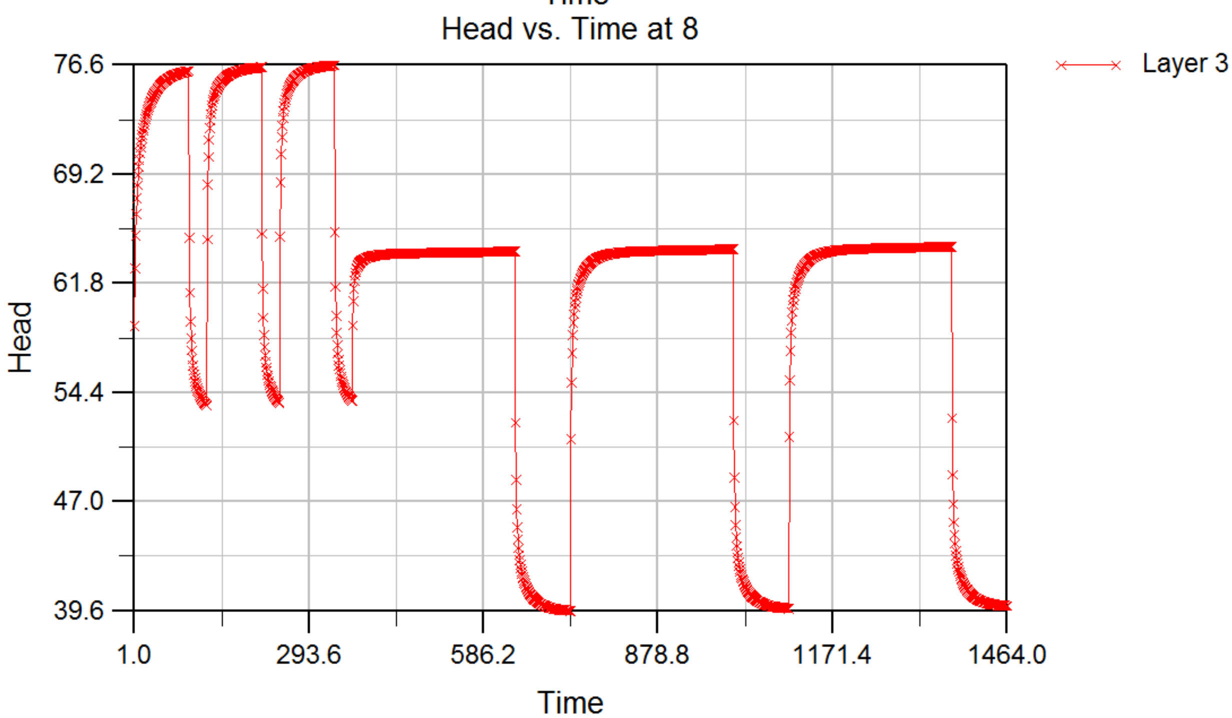


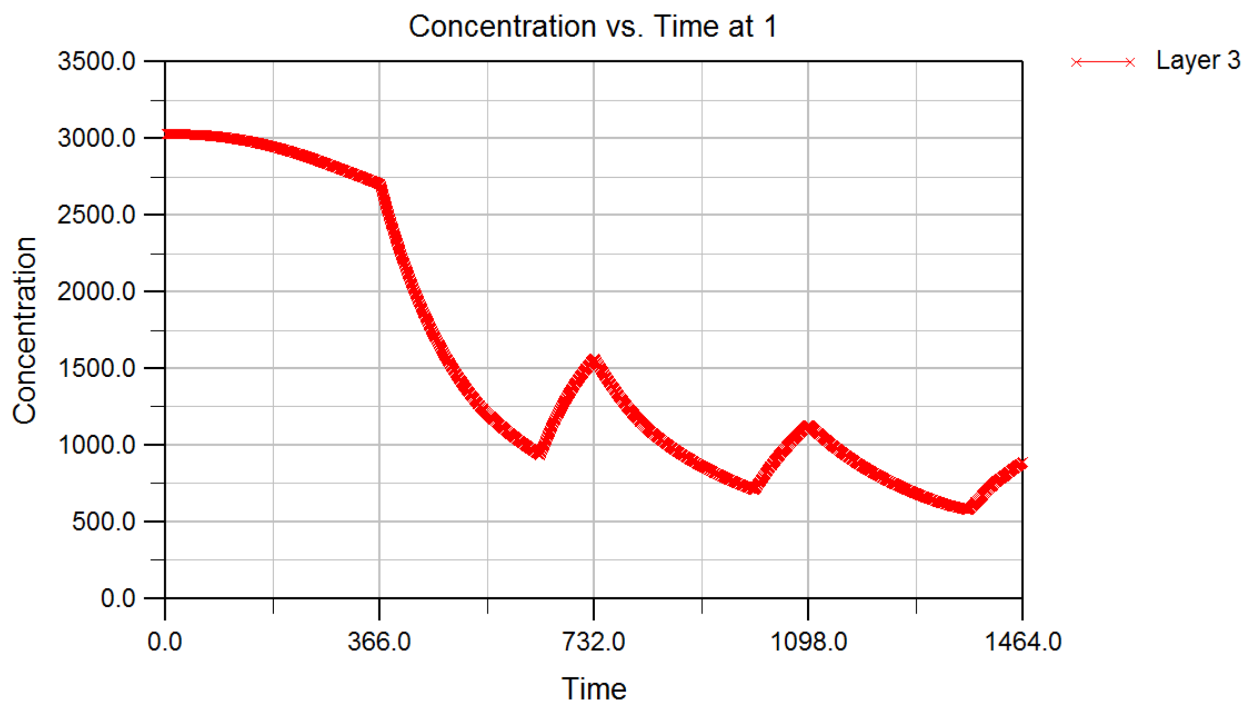
Head vs. Time at 5
Layer 3
77.7
69.8
61.9
54.0
46.2
38.3
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

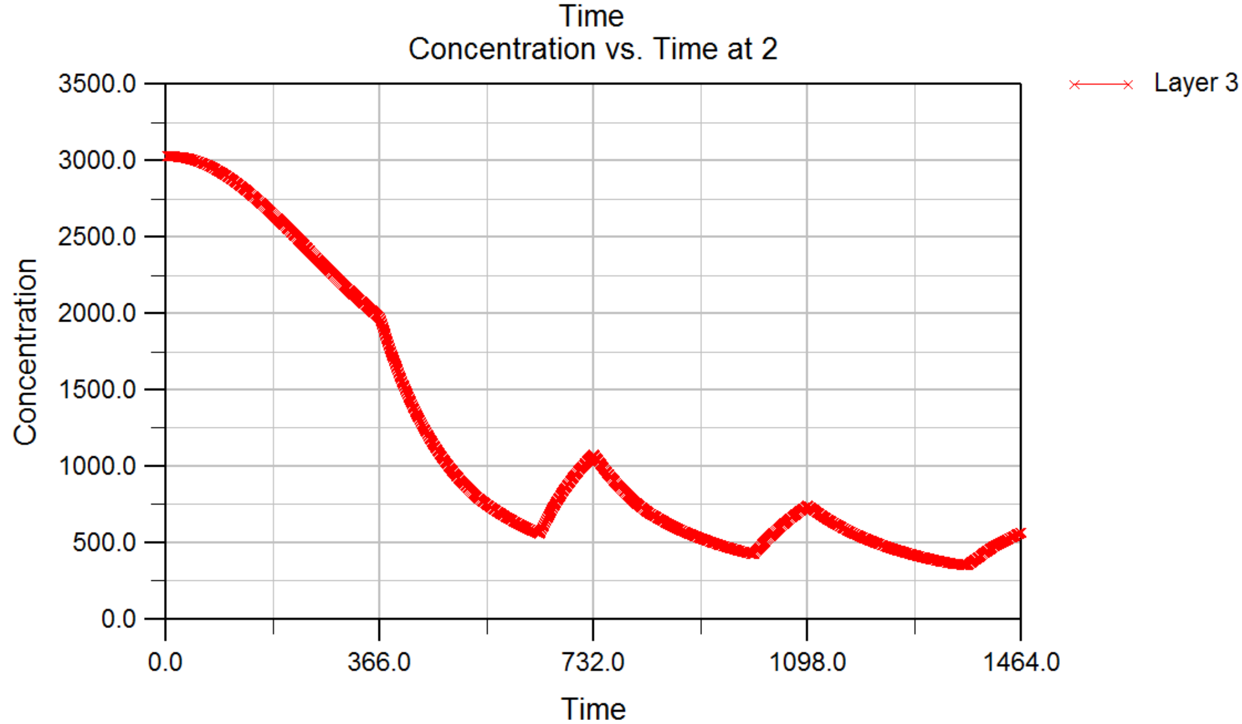


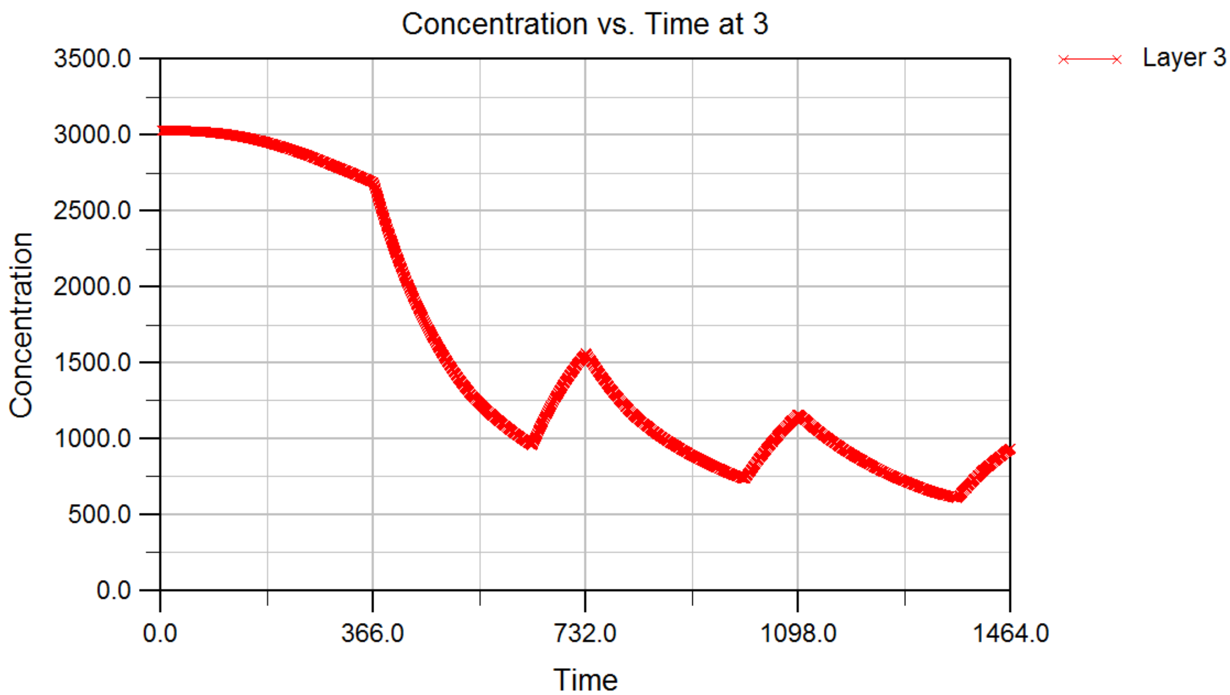
Head vs. Time at 6
Layer 3
75.7
68.9
62.1
55.3
48.4
41.6
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

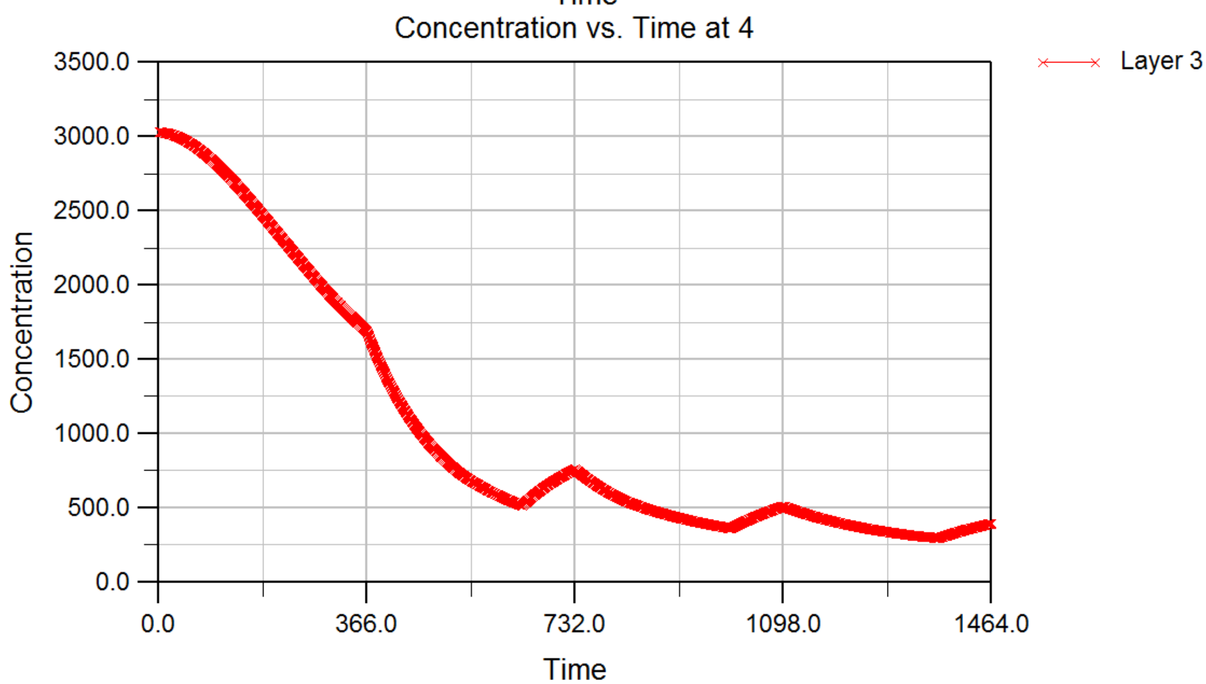

Head vs. Time at 7
Layer 3
77.1
69.7
62.2
54.8
47.4
39.9
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

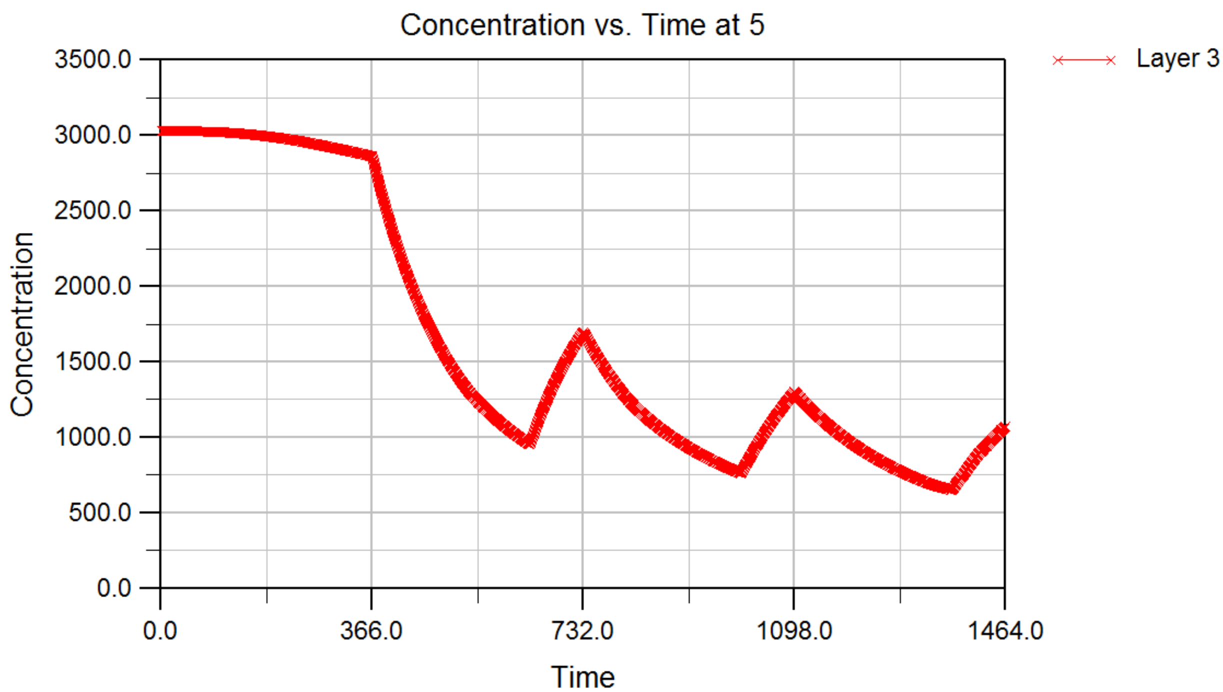

Head vs. Time at 8
Layer 3
76.6
69.2
61.8
54.4
47.0
39.6
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

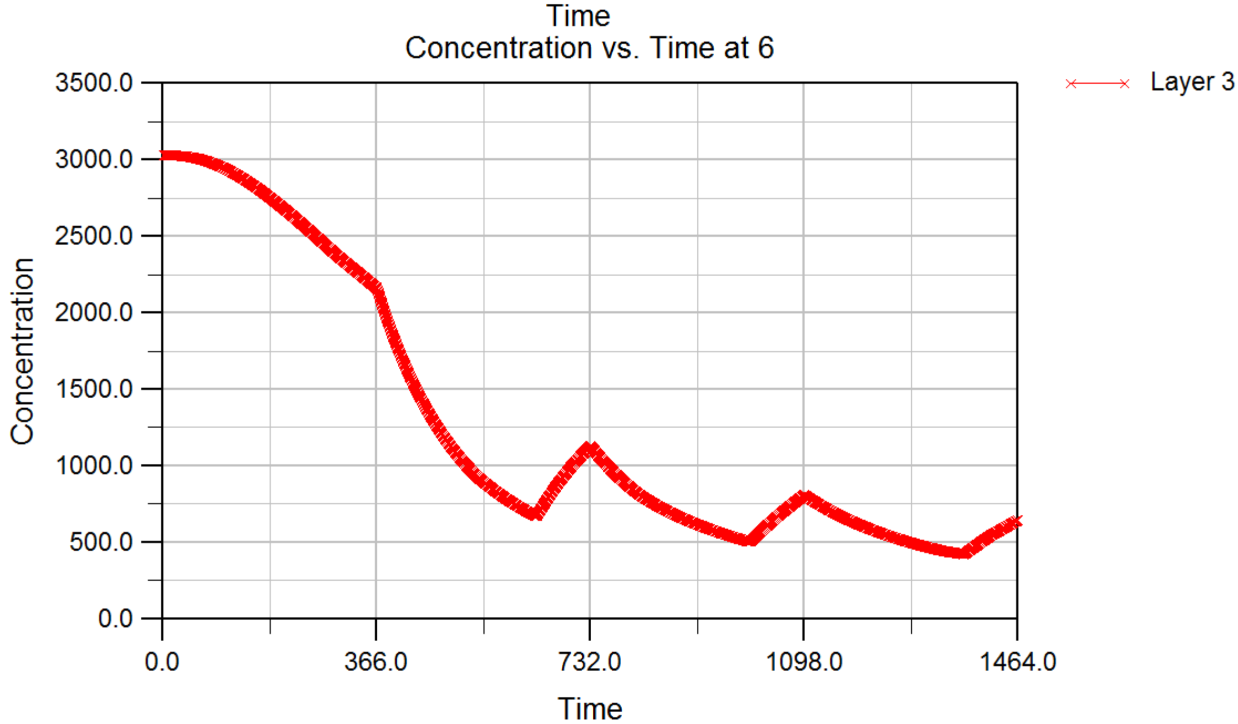

Concentration vs. Time at 1
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time

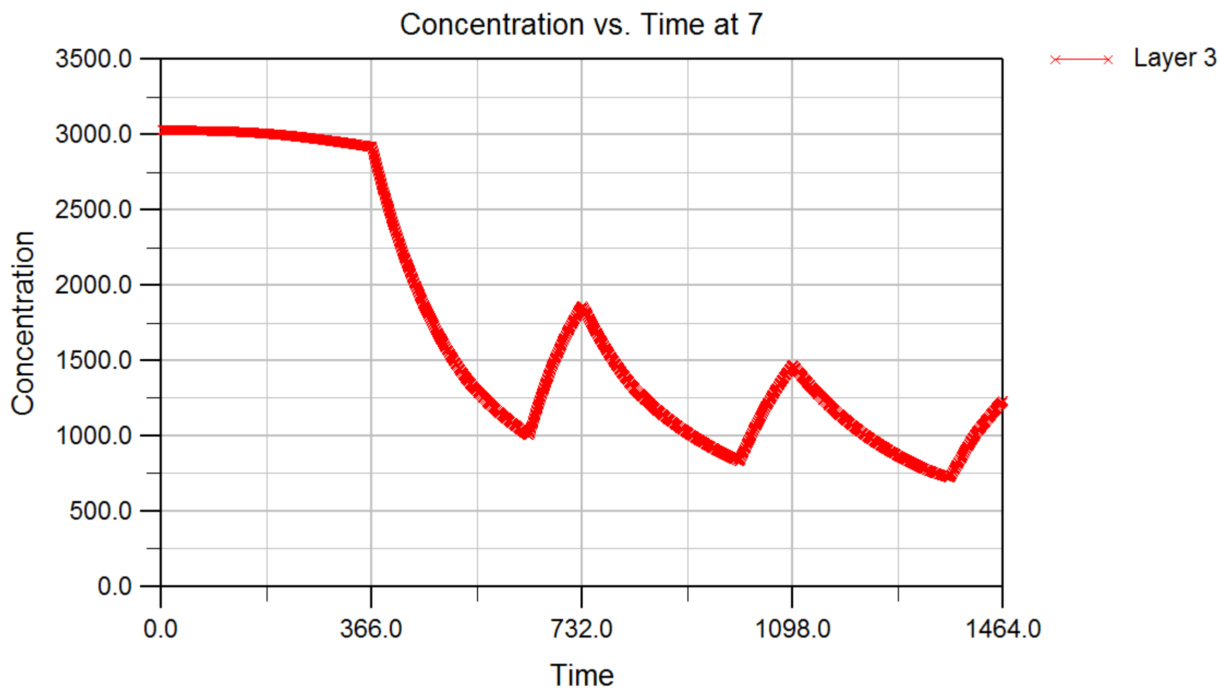

Concentration vs. Time at 2
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time

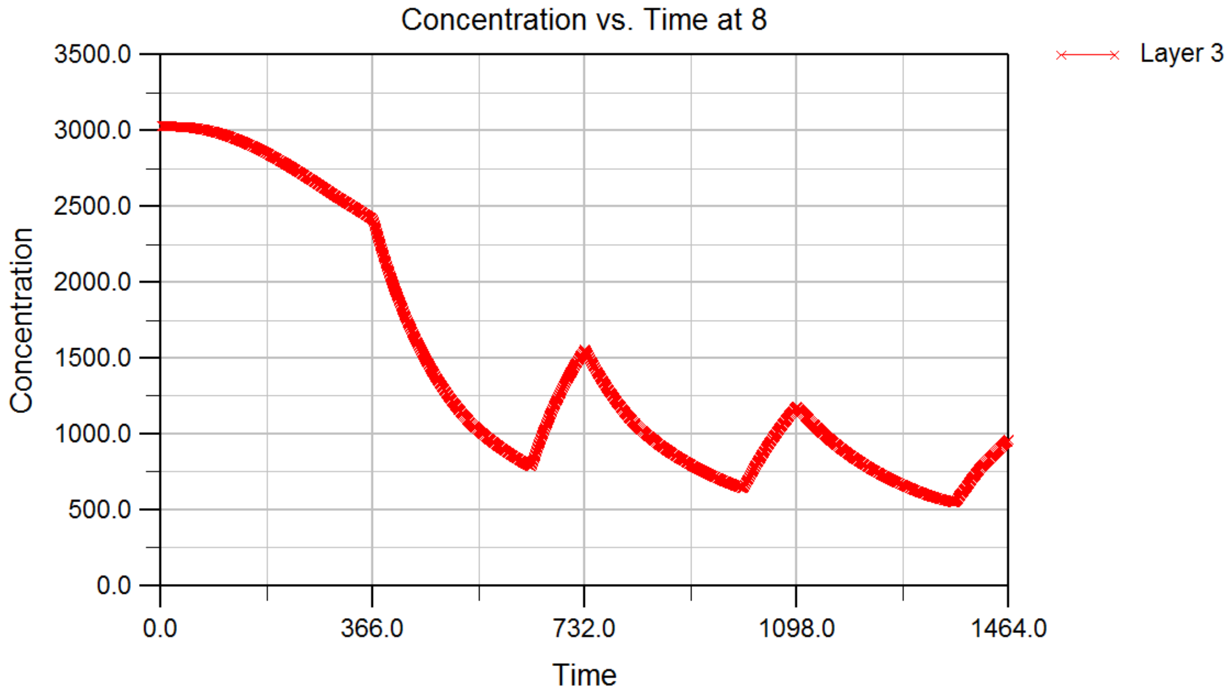

Concentration vs. Time at 3
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time


Concentration vs. Time at 4
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time

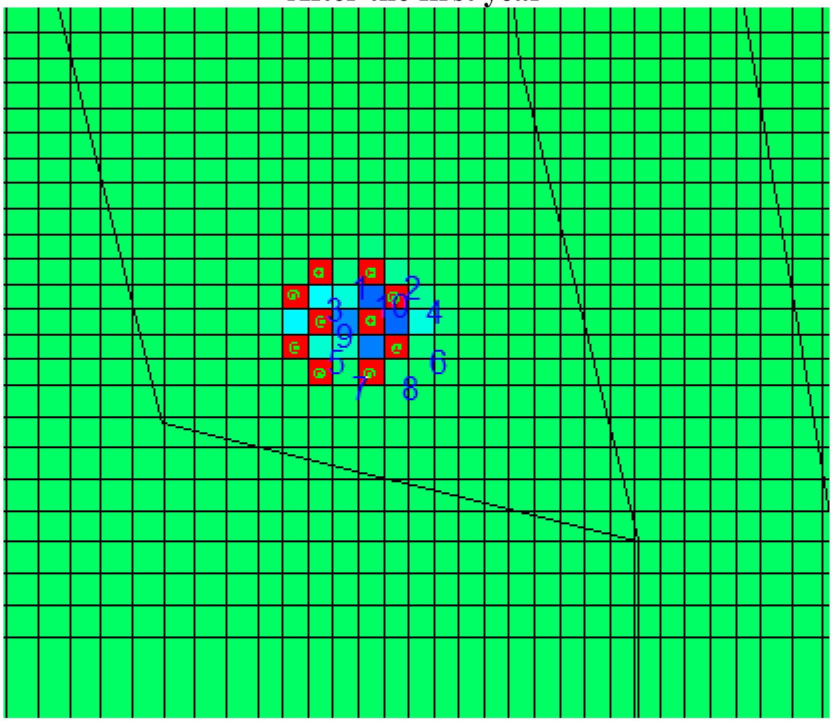

Concentration vs. Time at 5
Layer 3
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
Concentration
0.0
366.0
732.0
1098.0
1464.0
Time

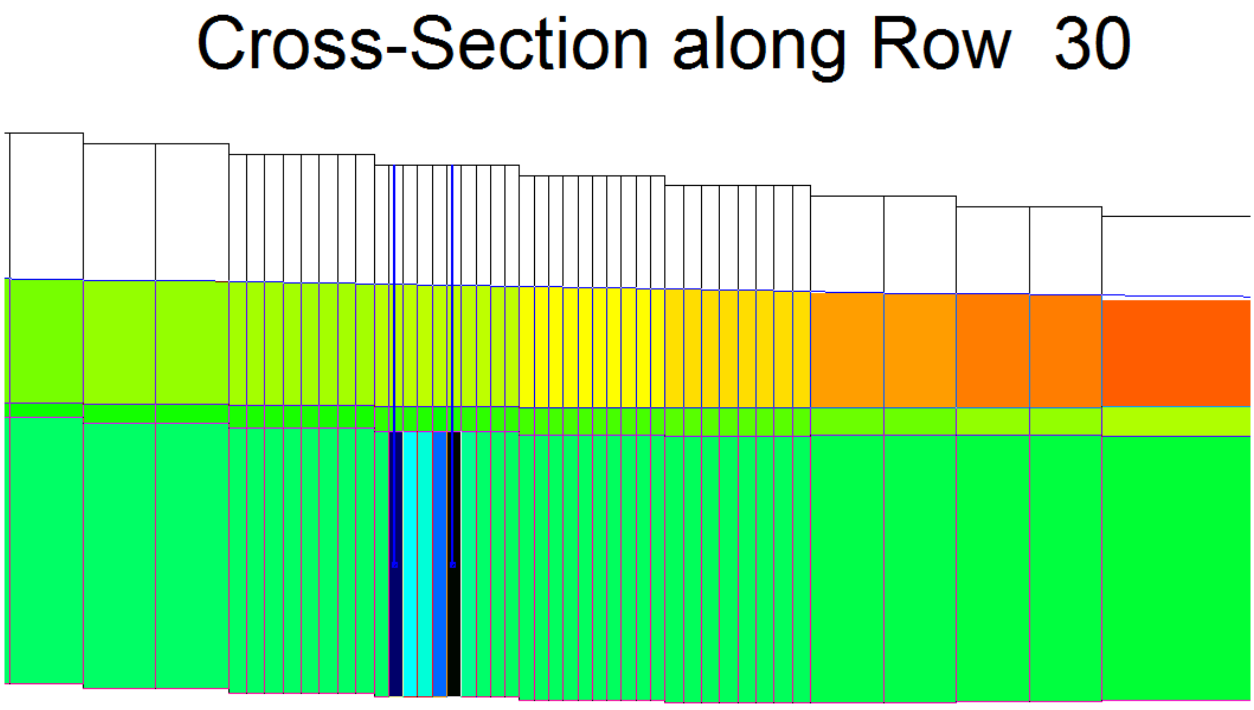

Concentration vs. Time at 6
Layer 3
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
Concentration
0.0
366.0
732.0
1098.0
1464.0
Time


Concentration vs. Time at 7
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time

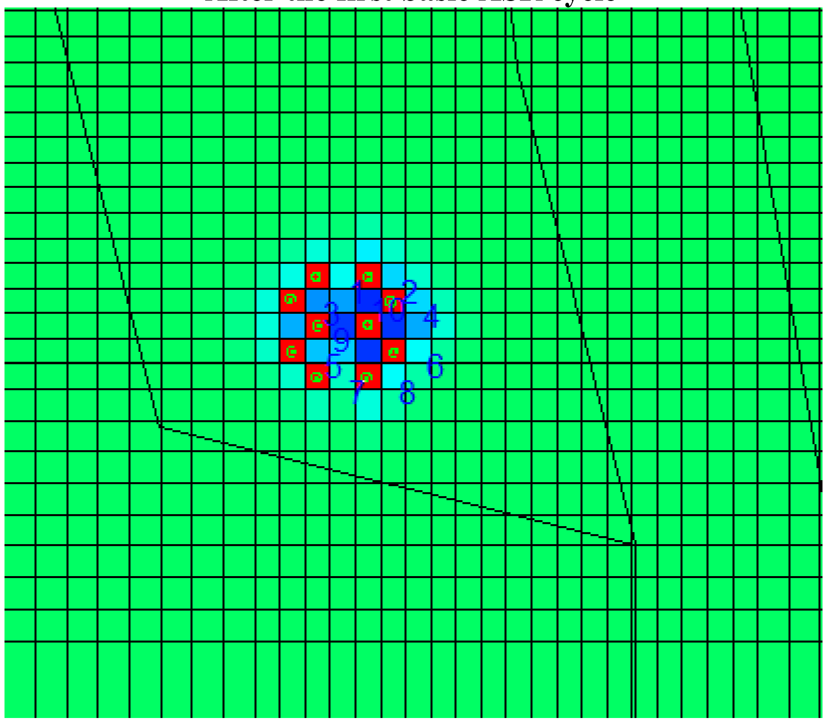

Concentration vs. Time at 8
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time

After the first year

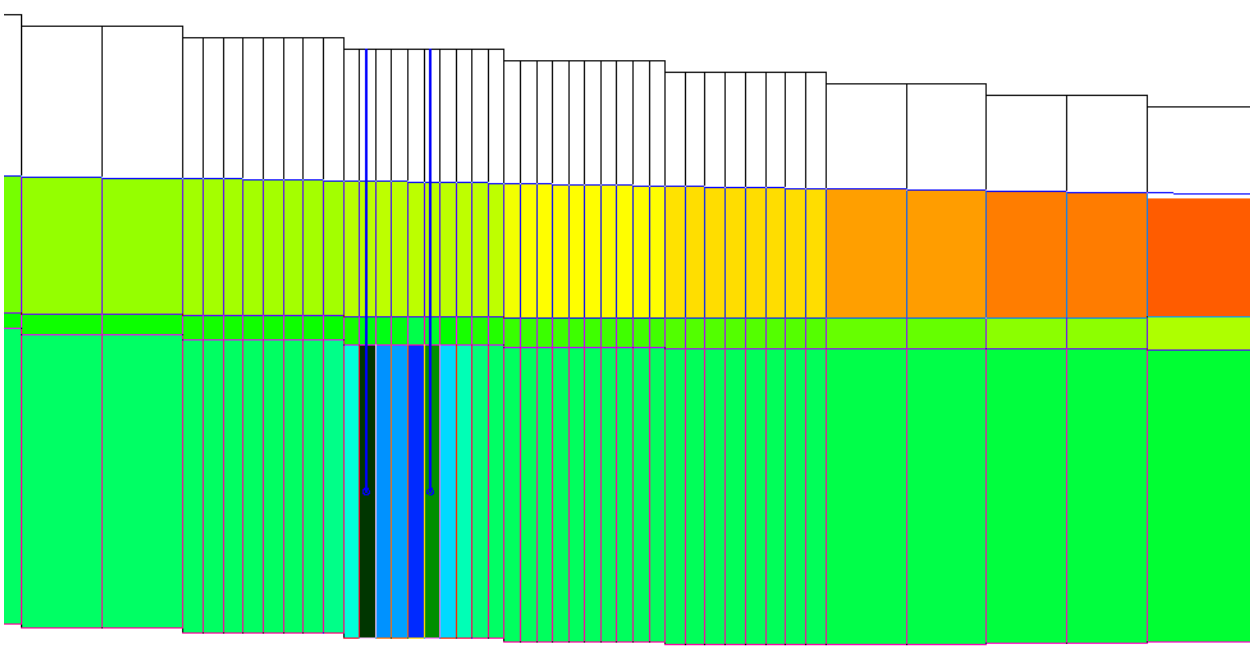




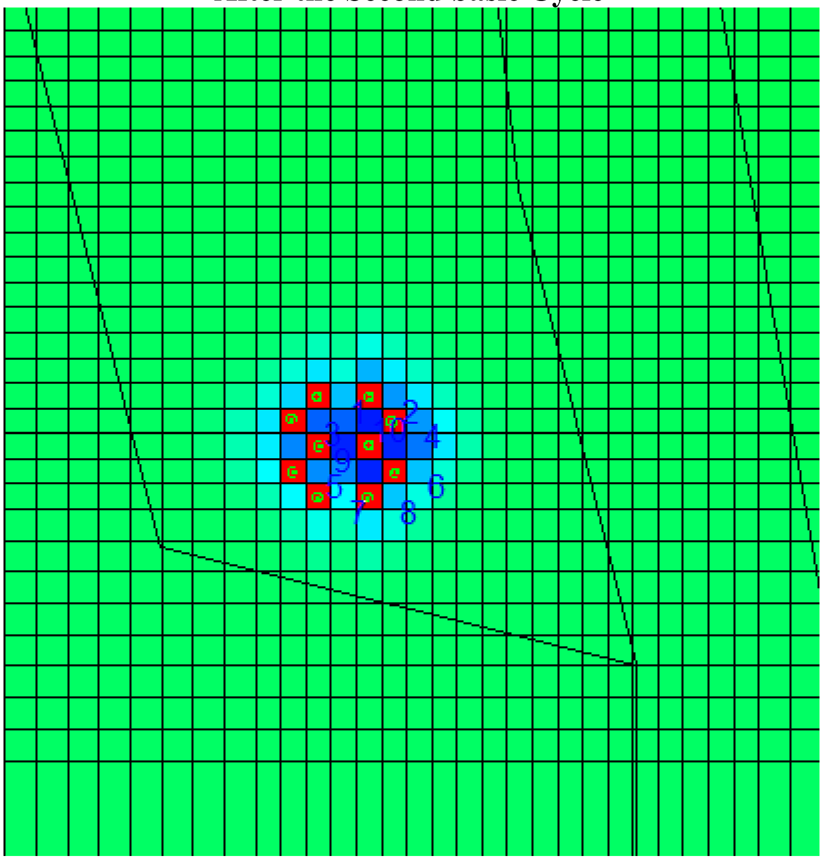
After the first basic ASR cycle



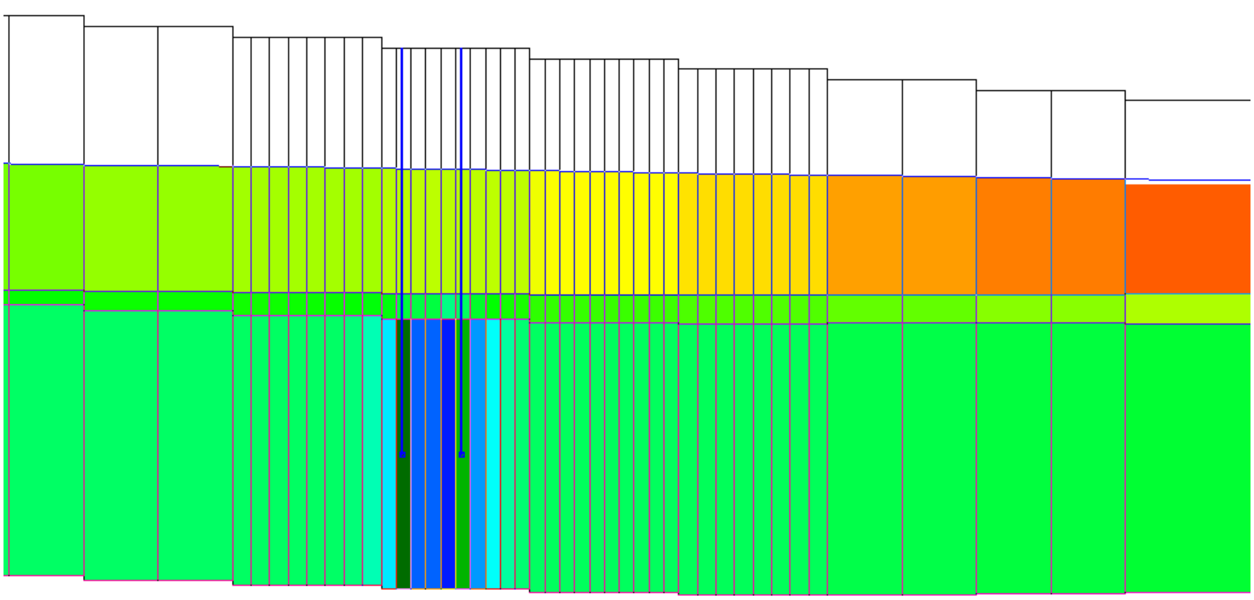
Cross-Section along Row 30



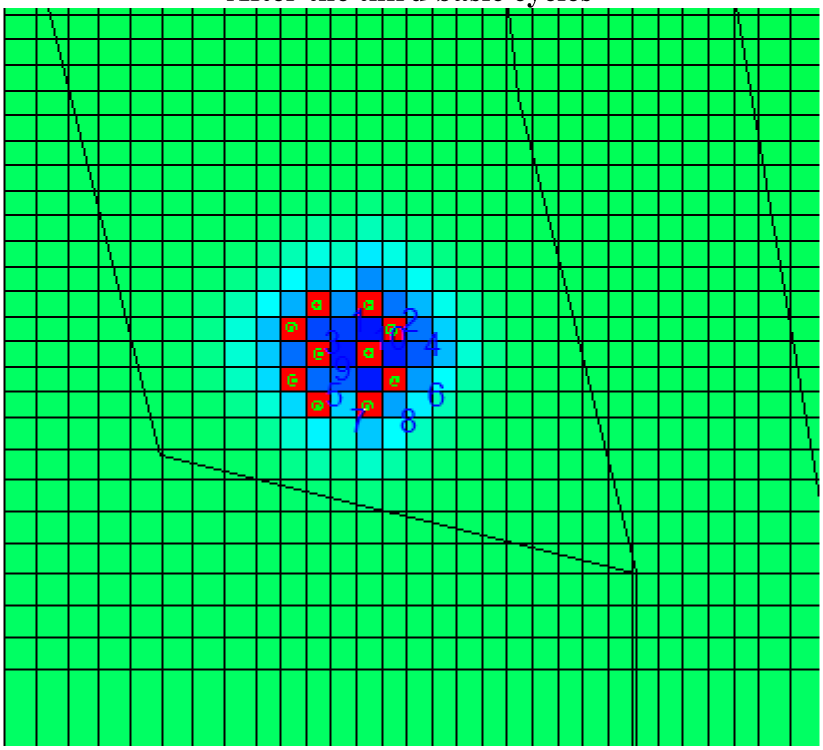
After the Second basic Cycle



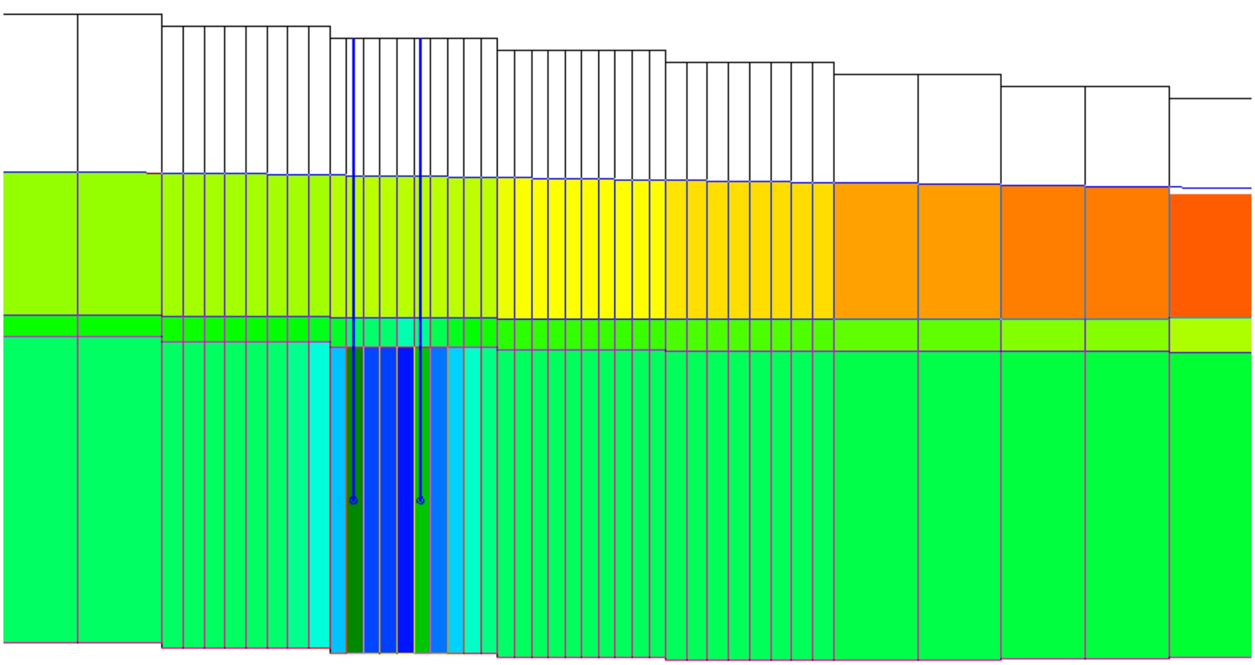
Cross-Section along Row 30



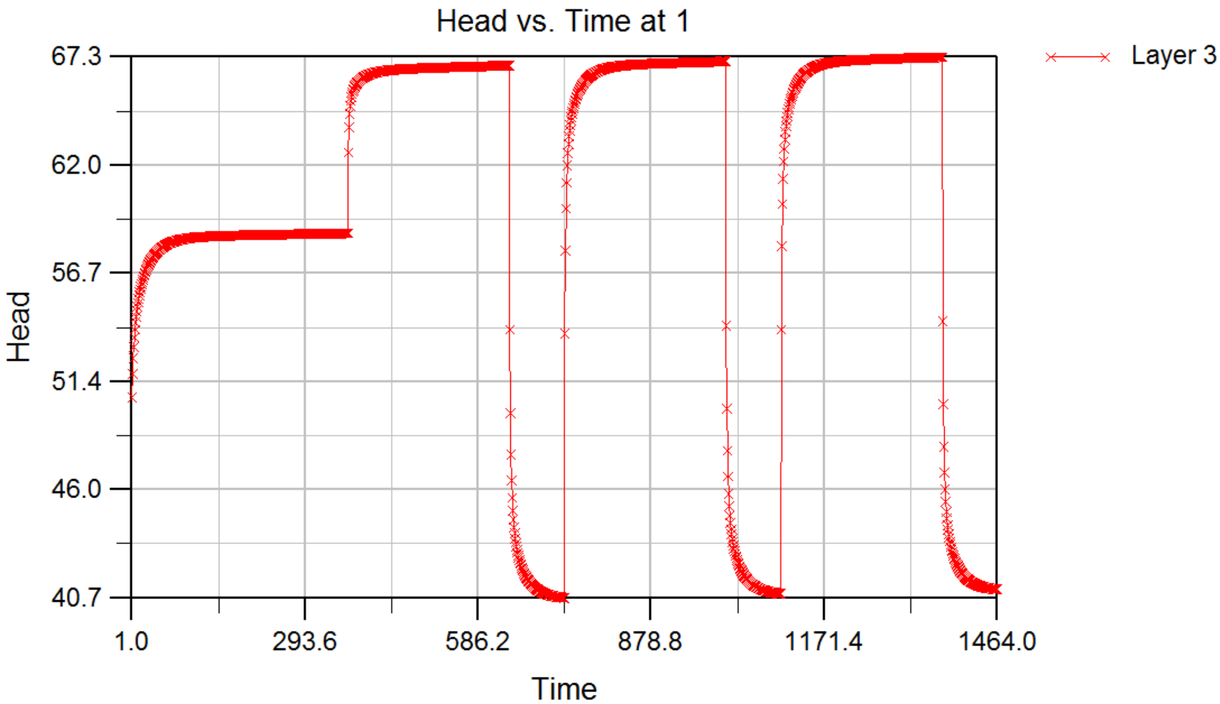
After the third basic cycles

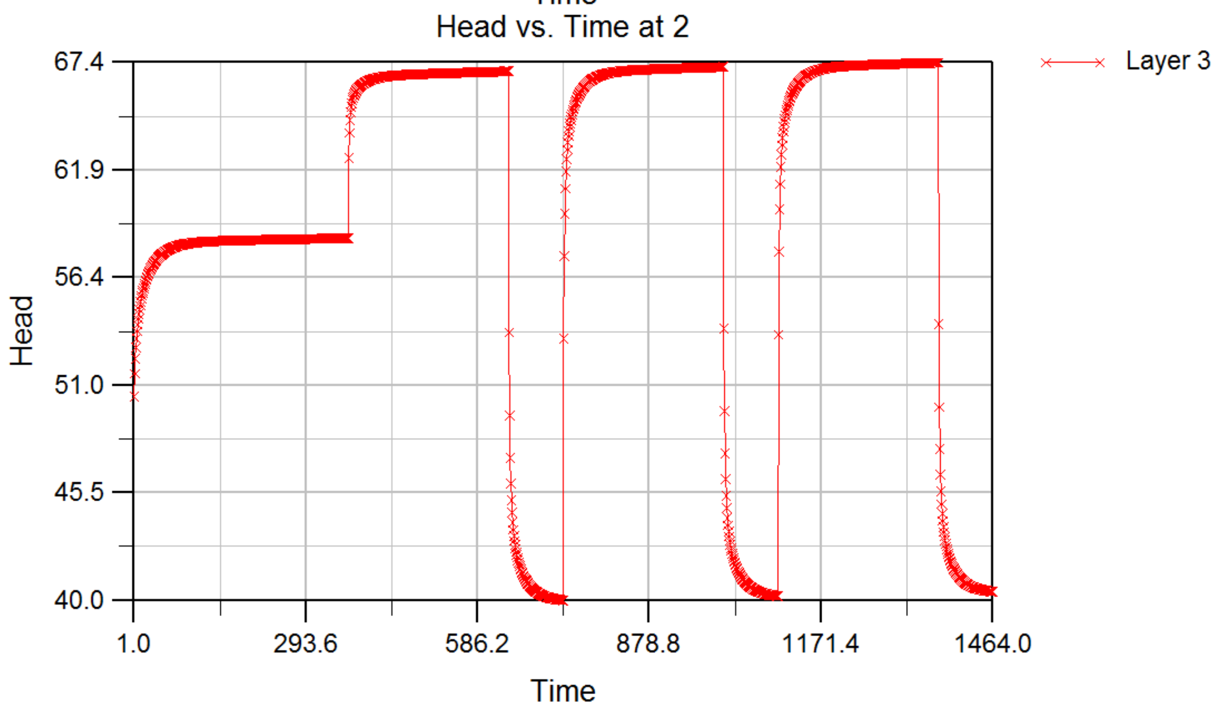


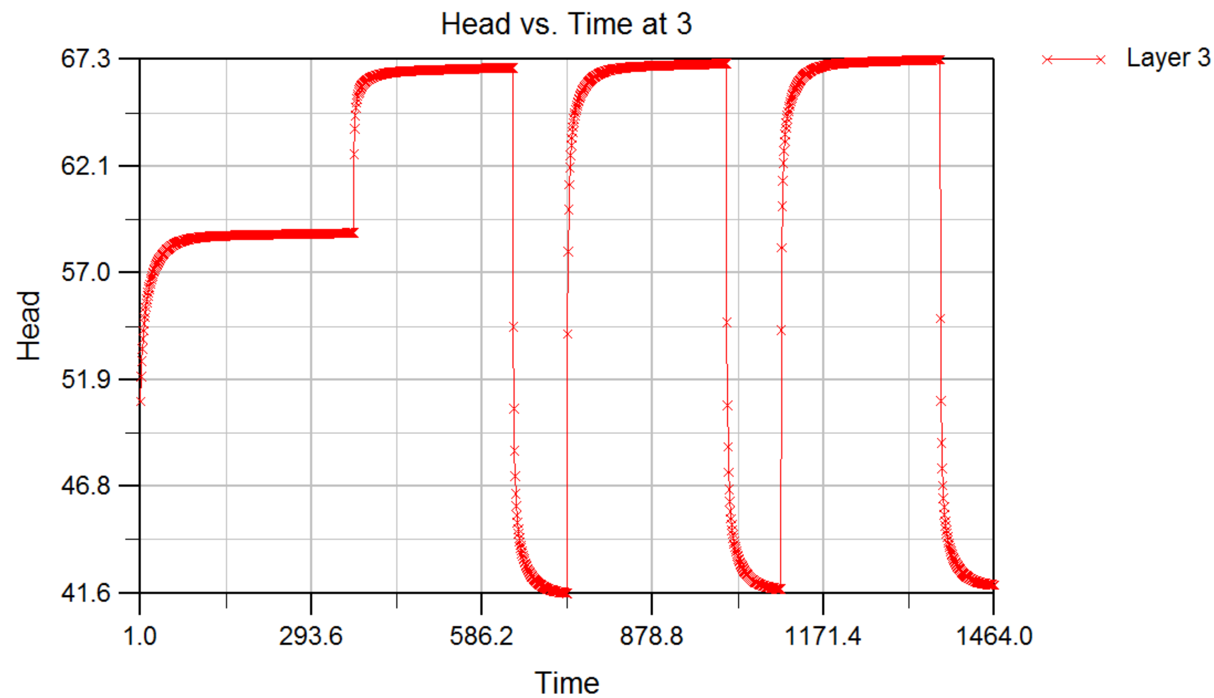
Cross-Section along Row 30

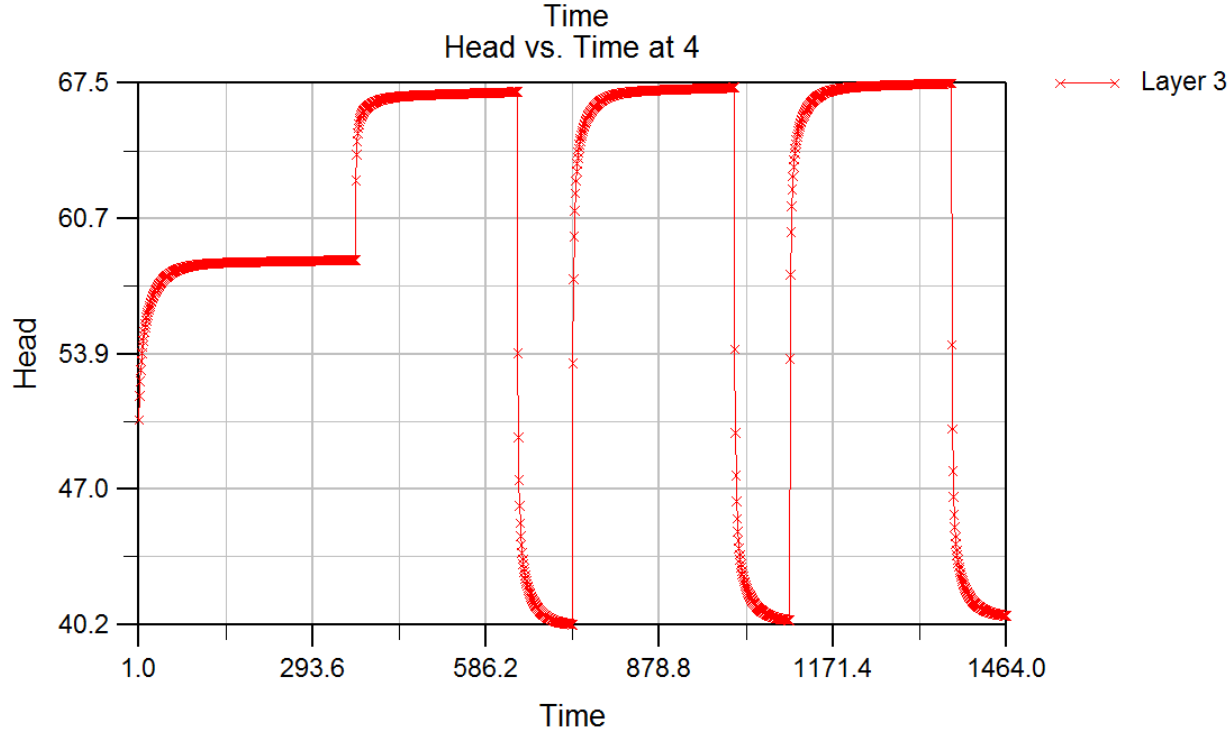


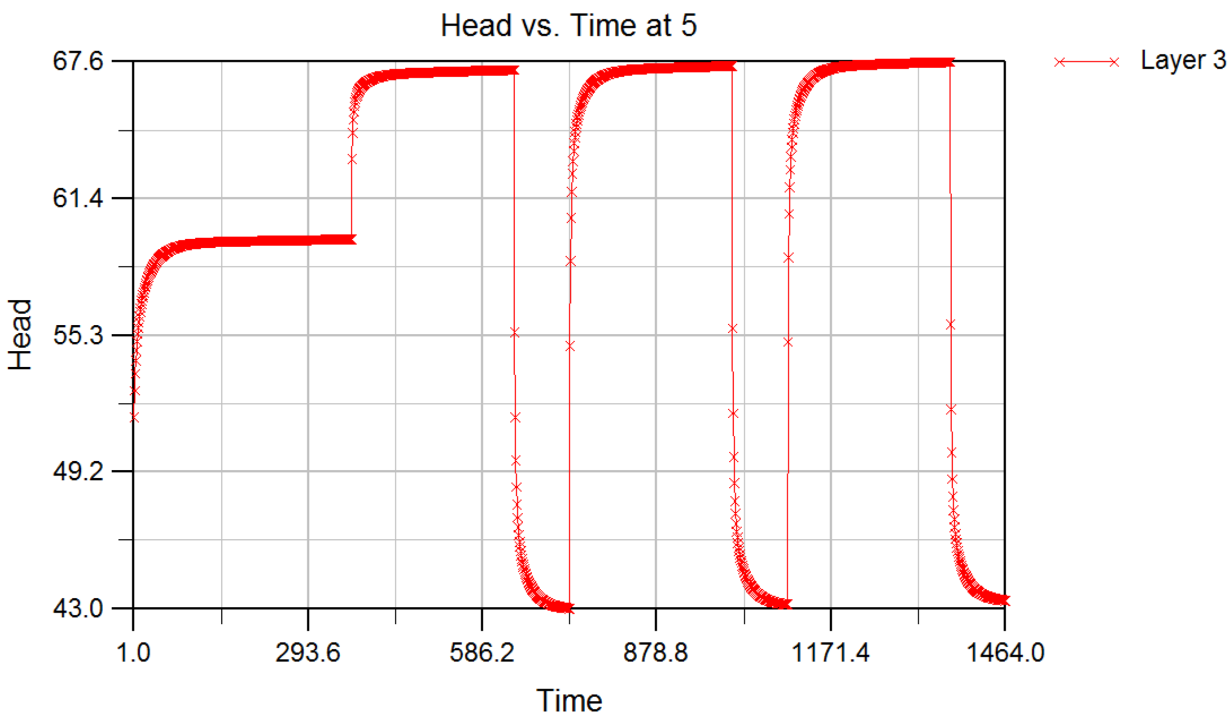
RUN 10

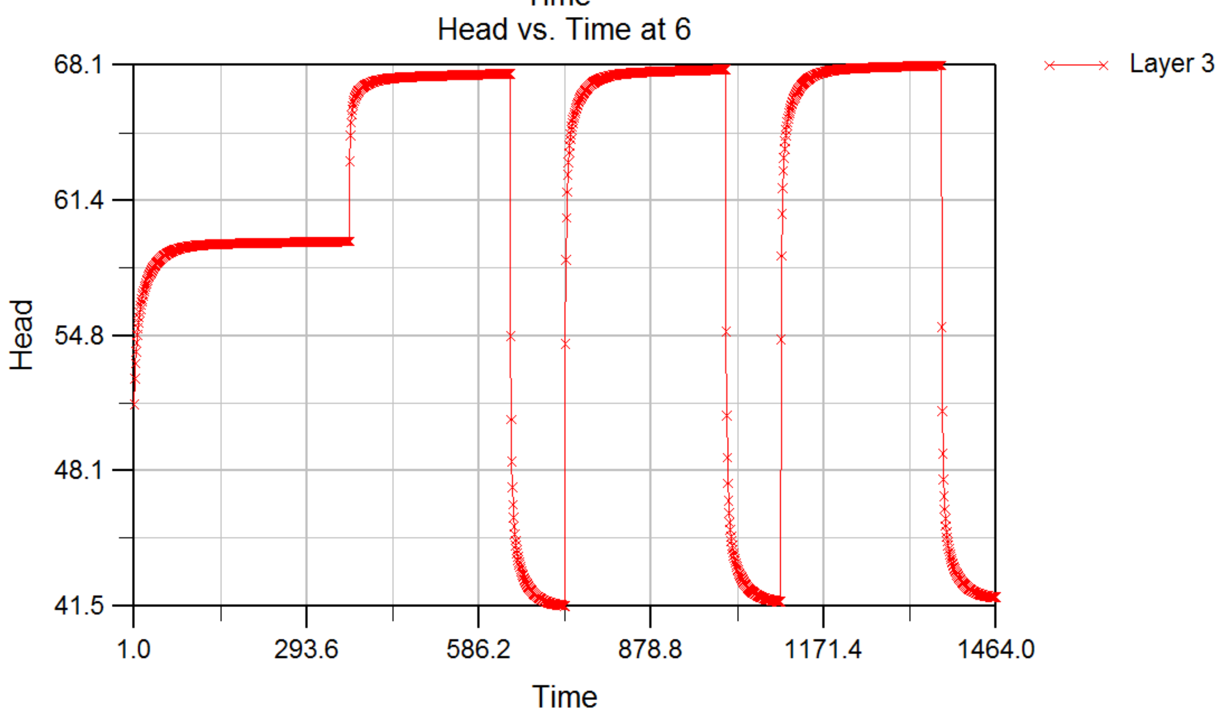

Head vs. Time at 1
67.3
62.0
56.7
51.4
46.0
40.7
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time
Layer 3

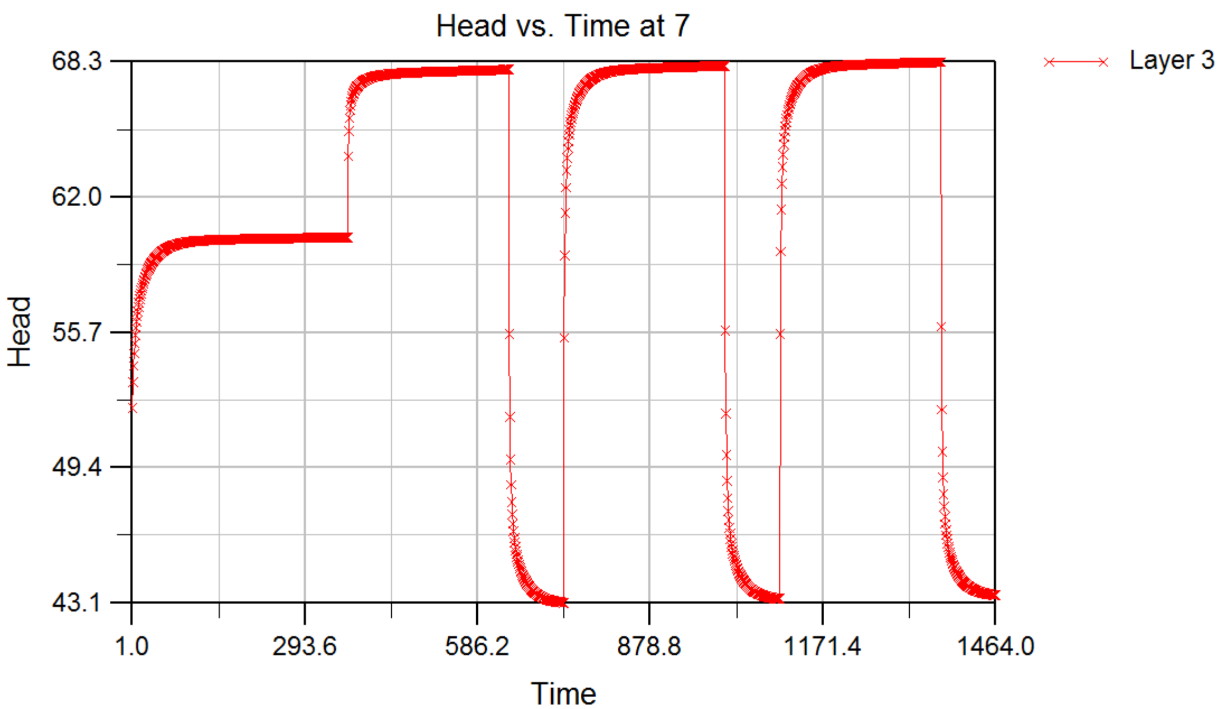

Head vs. Time at 2
67.4
61.9
56.4
51.0
45.5
40.0
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time
Layer 3

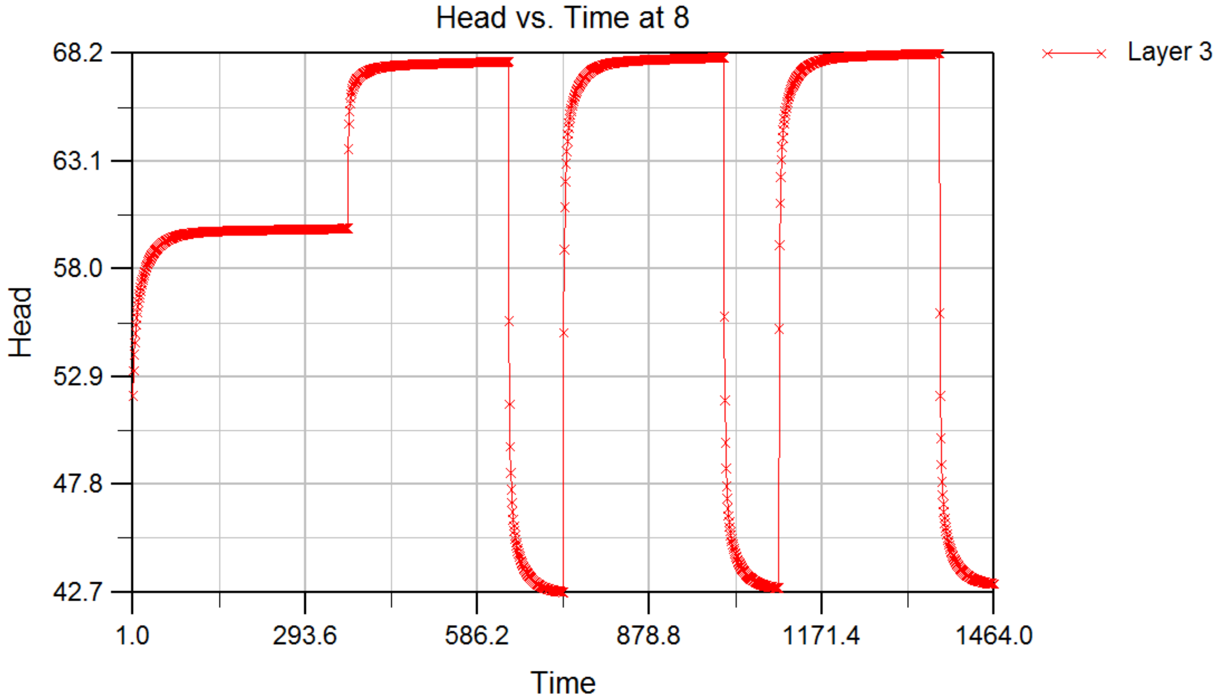

Head vs. Time at 3
Layer 3
67.3
62.1
57.0
51.9
46.8
41.6
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time


Head vs. Time at 4
Layer 3
67.5
60.7
53.9
47.0
40.2
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

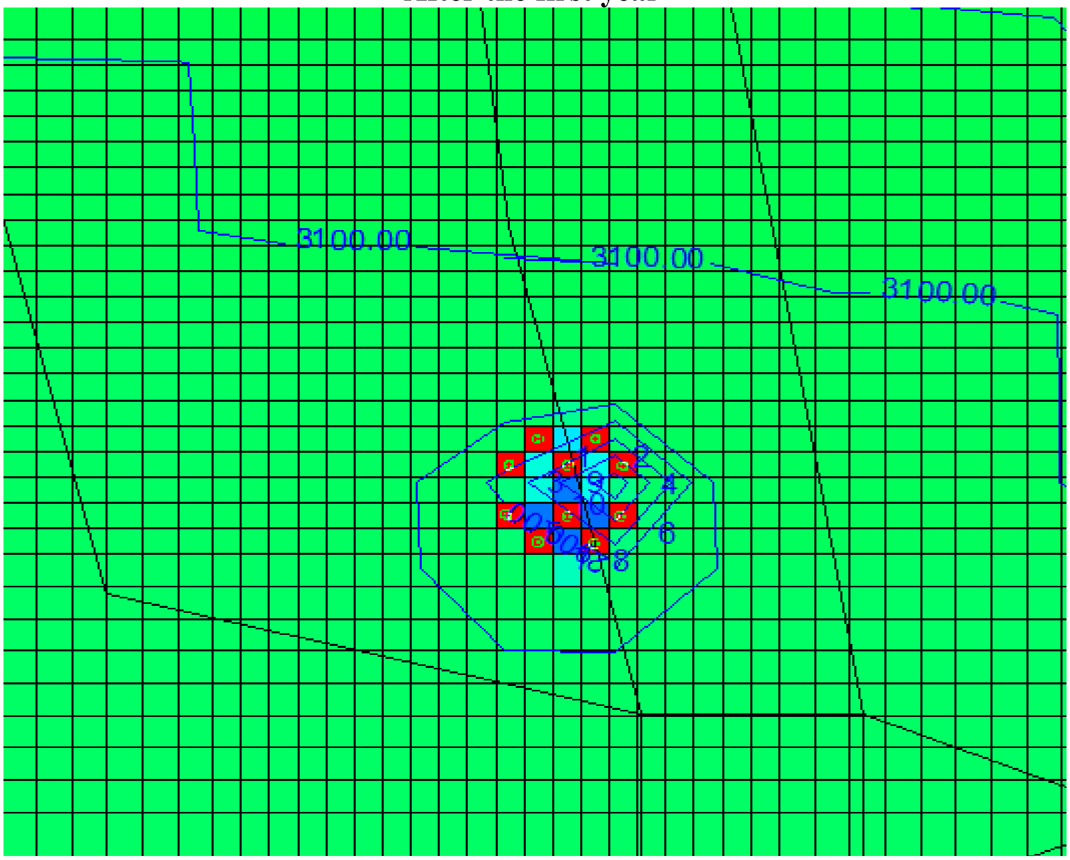

Head vs. Time at 5
Layer 3
67.6
61.4
55.3
49.2
43.0
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time


Head vs. Time at 6
Layer 3
68.1
61.4
54.8
48.1
41.5
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

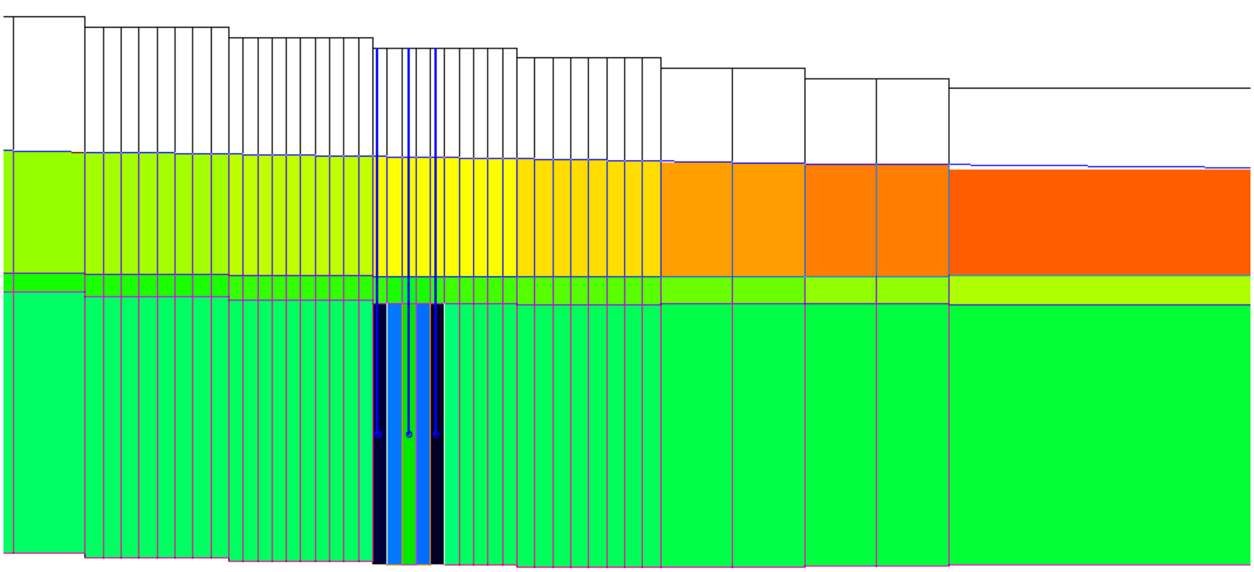

Head vs. Time at 7
Layer 3
68.3
62.0
55.7
49.4
43.1
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time


Head vs. Time at 8
Layer 3
68.2
63.1
58.0
52.9
47.8
42.7
Head
1.0
293.6
586.2
878.8
1171.4
1464.0
Time

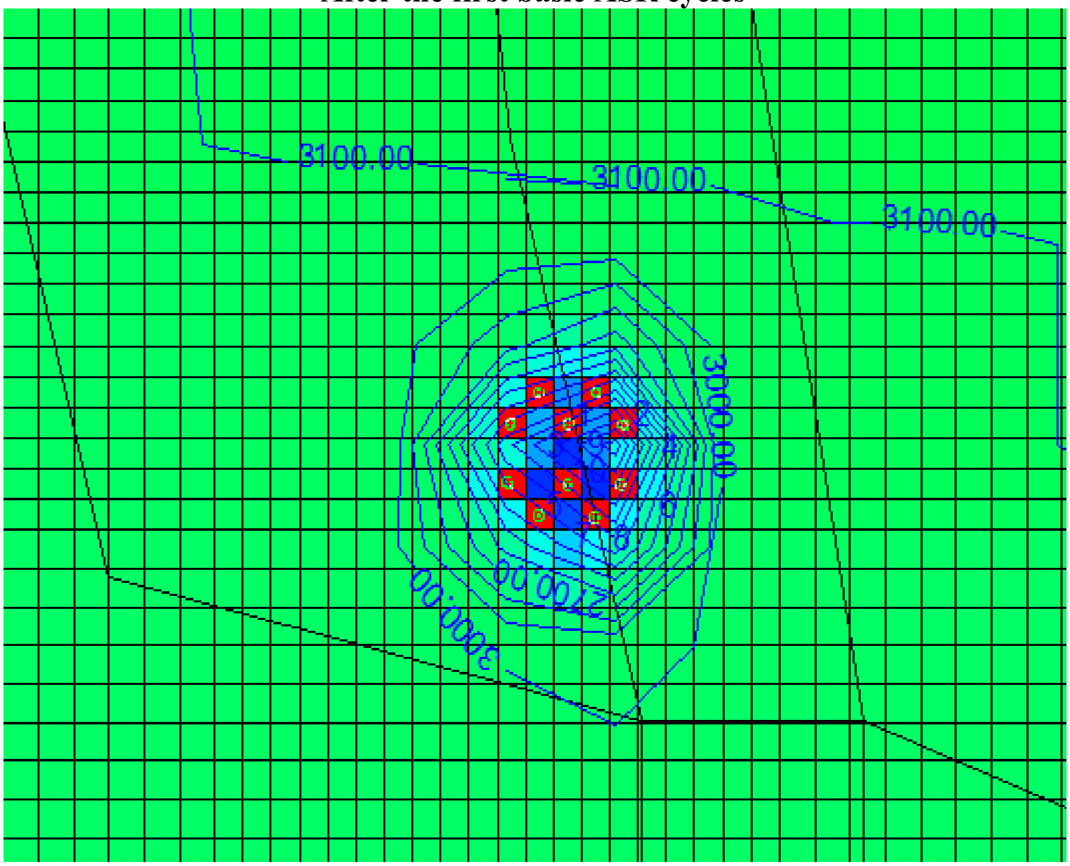
After the first year



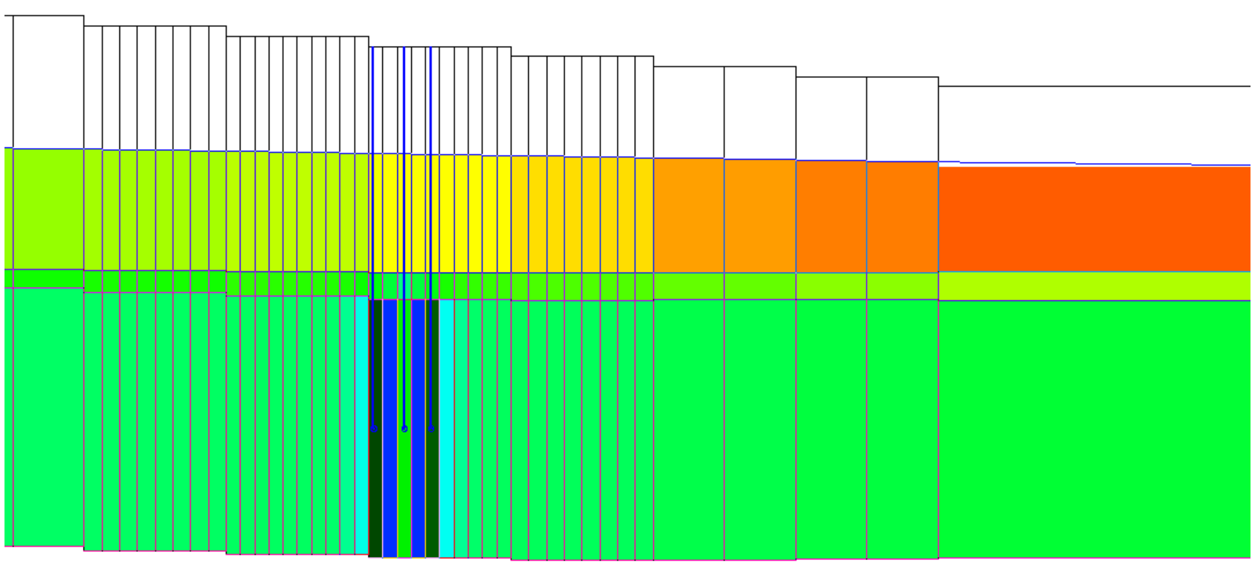
Cross-Section along Row 32



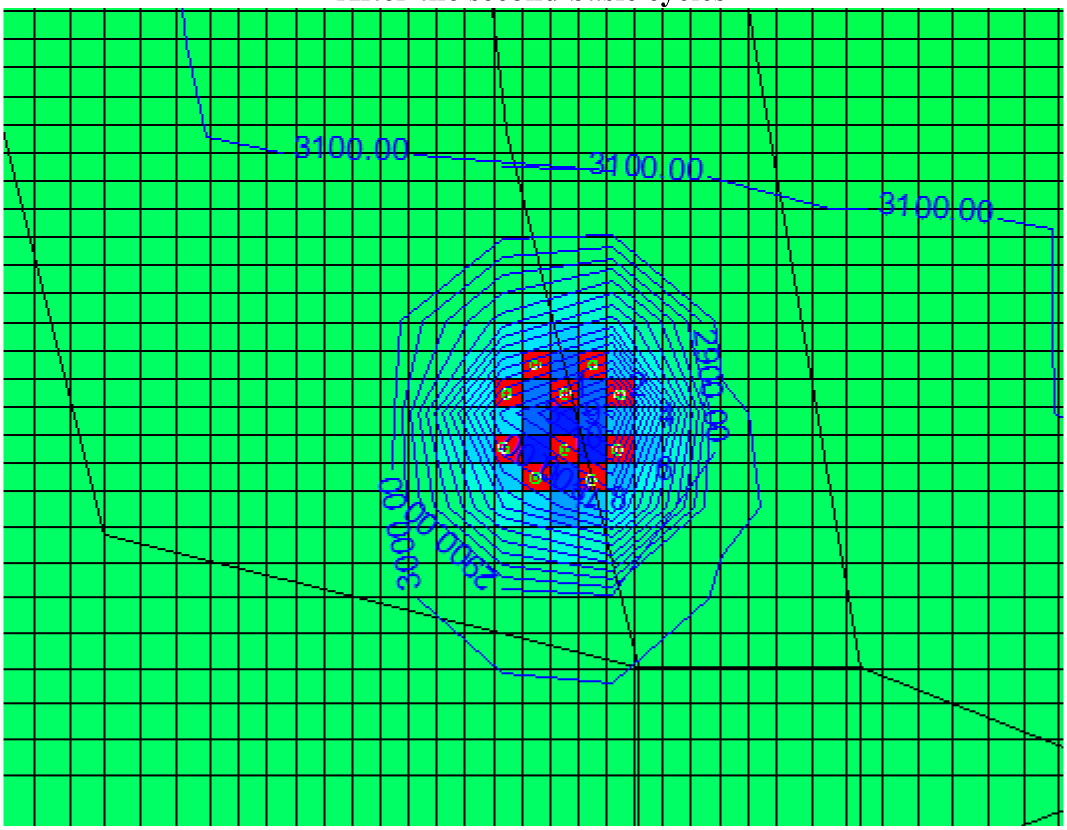
After the first basic ASR cycles



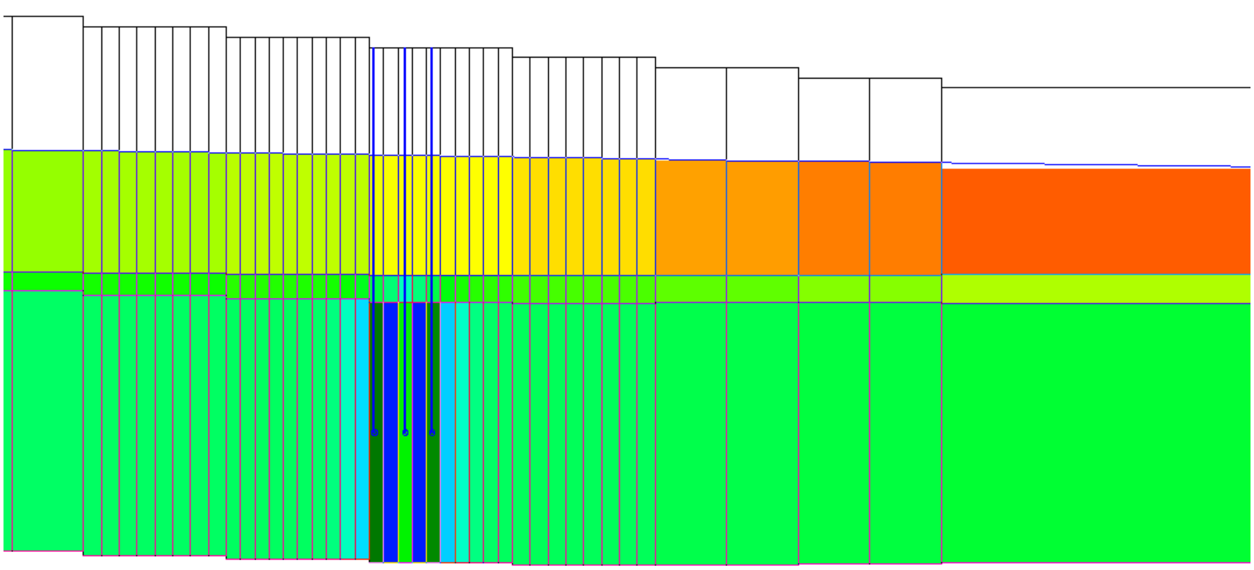
Cross-Section along Row 32



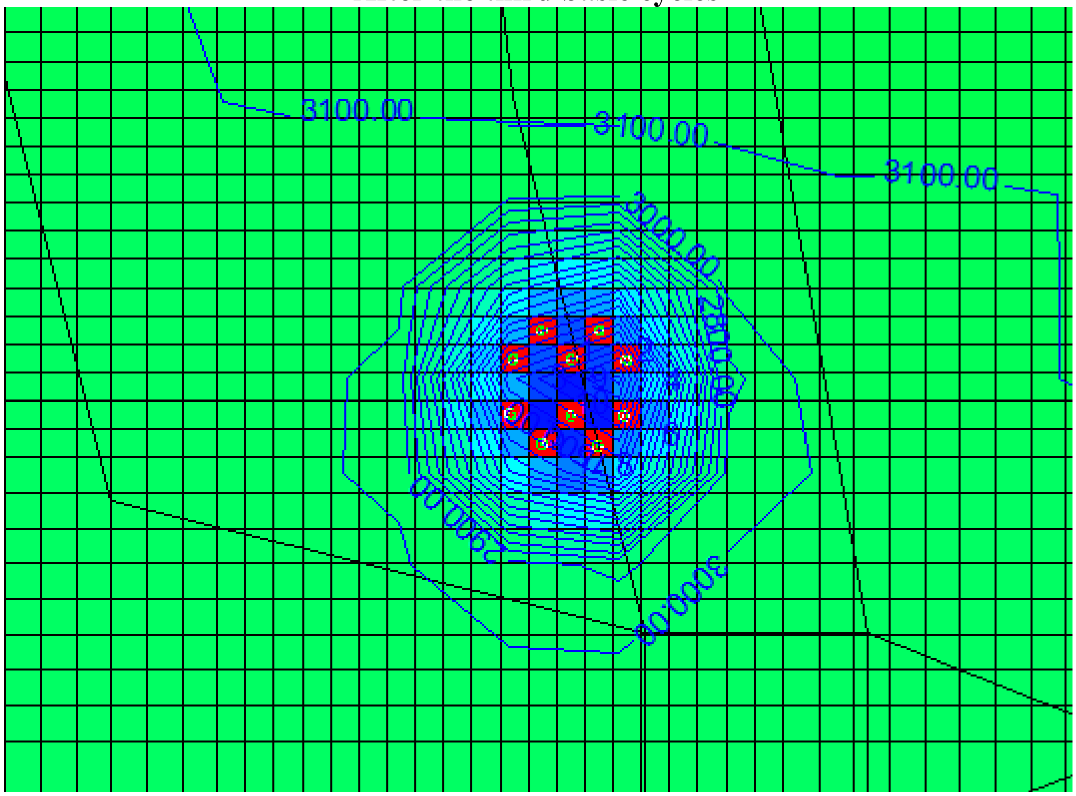
After the second basic cycles



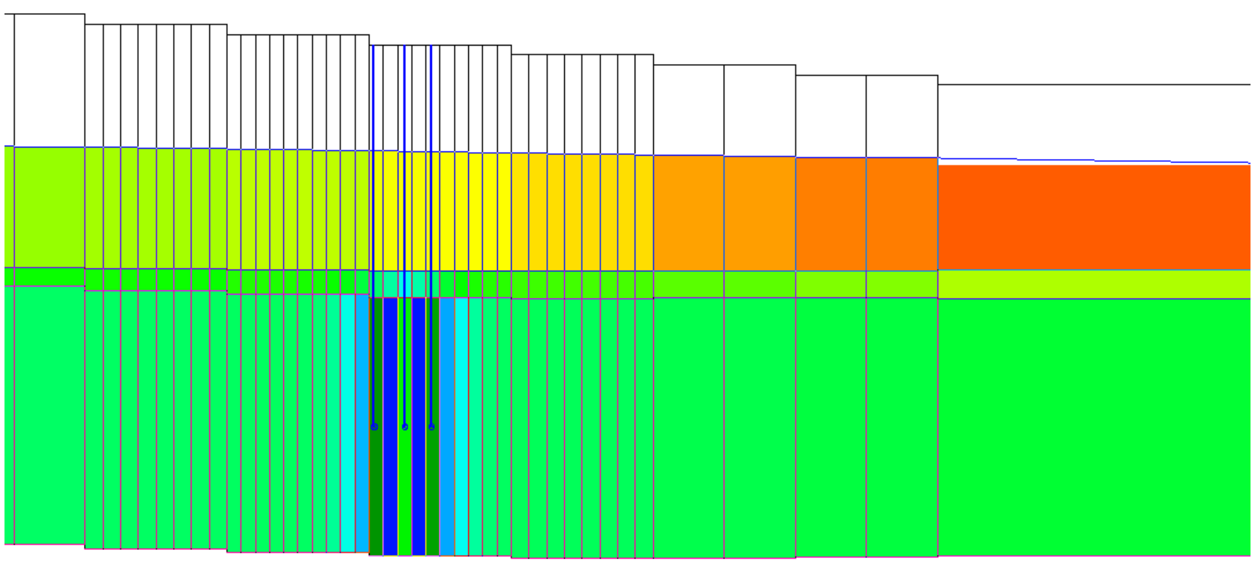
Cross-Section along Row 32

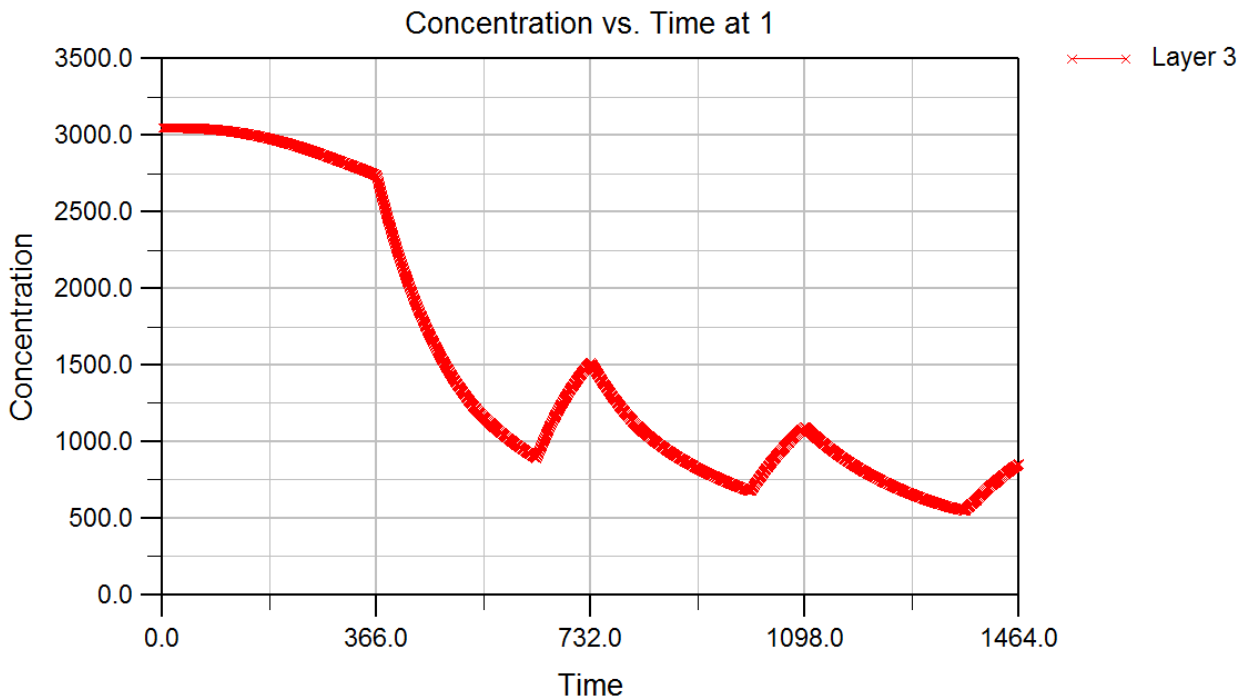


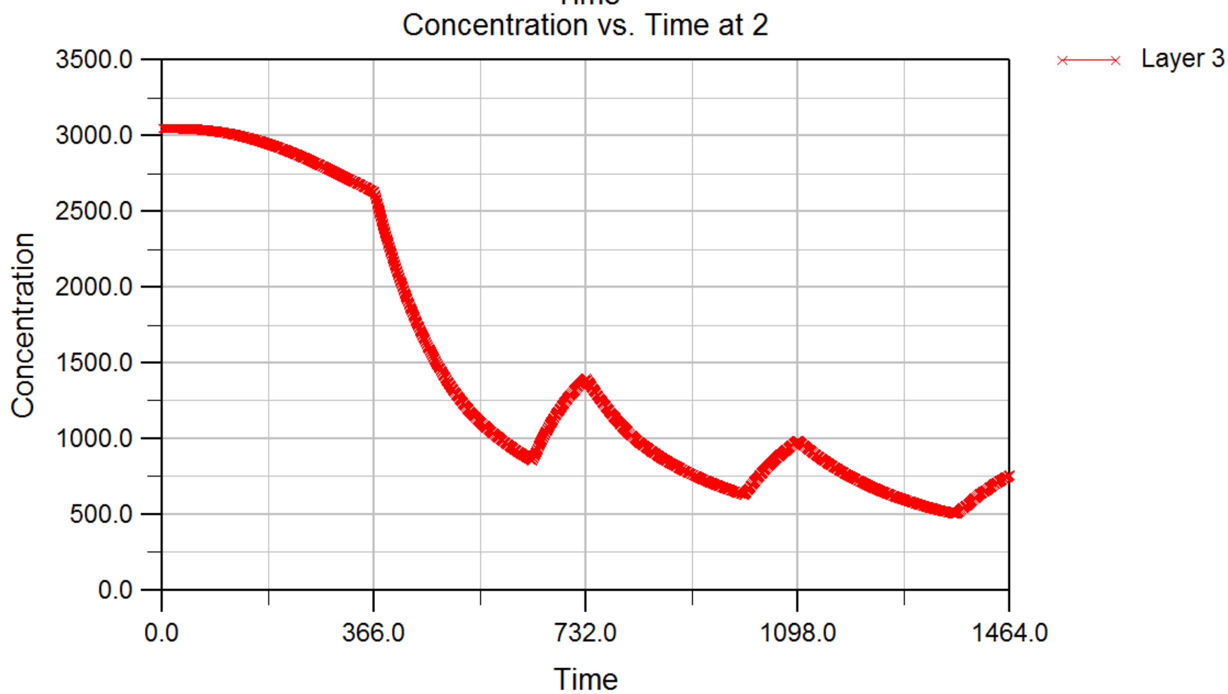
After the third basic cycles

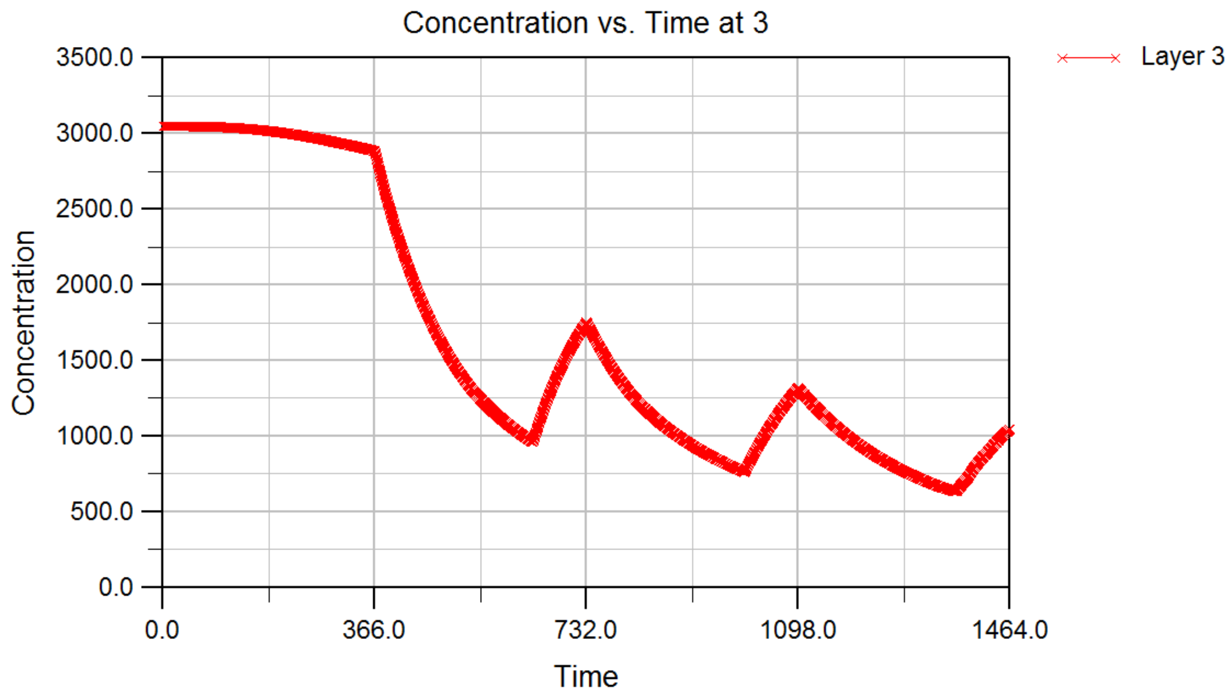


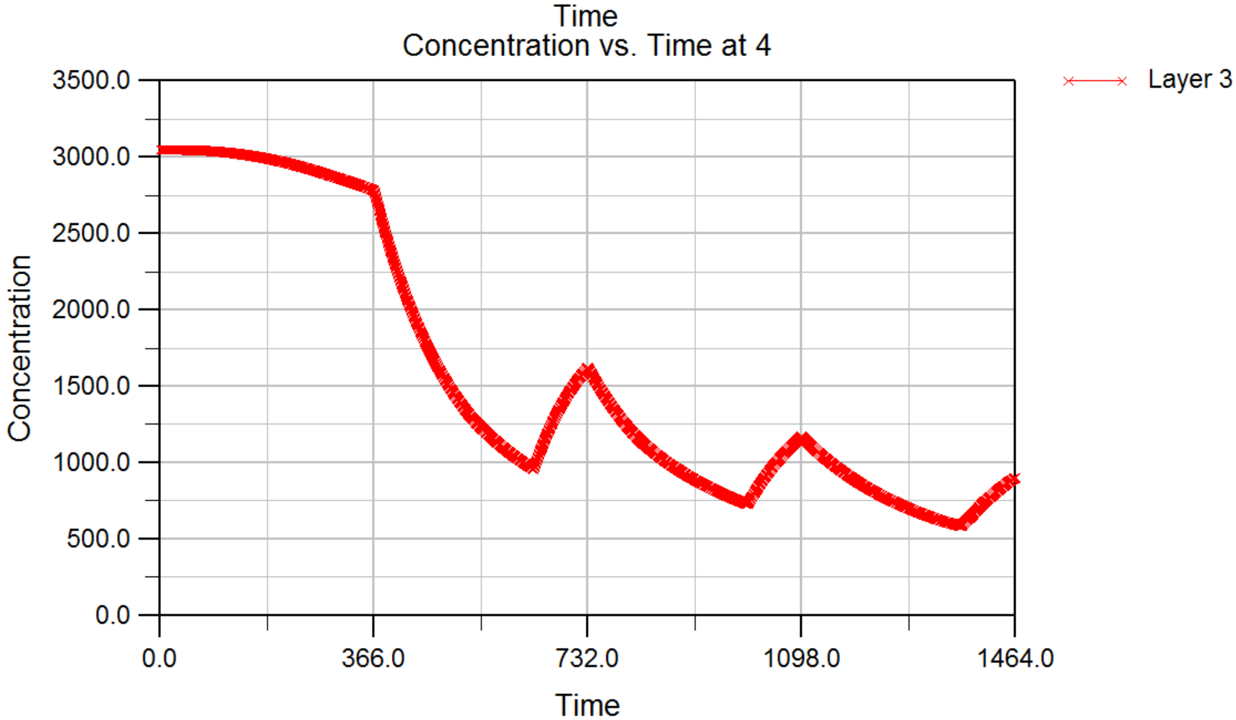
Cross-Section along Row 32

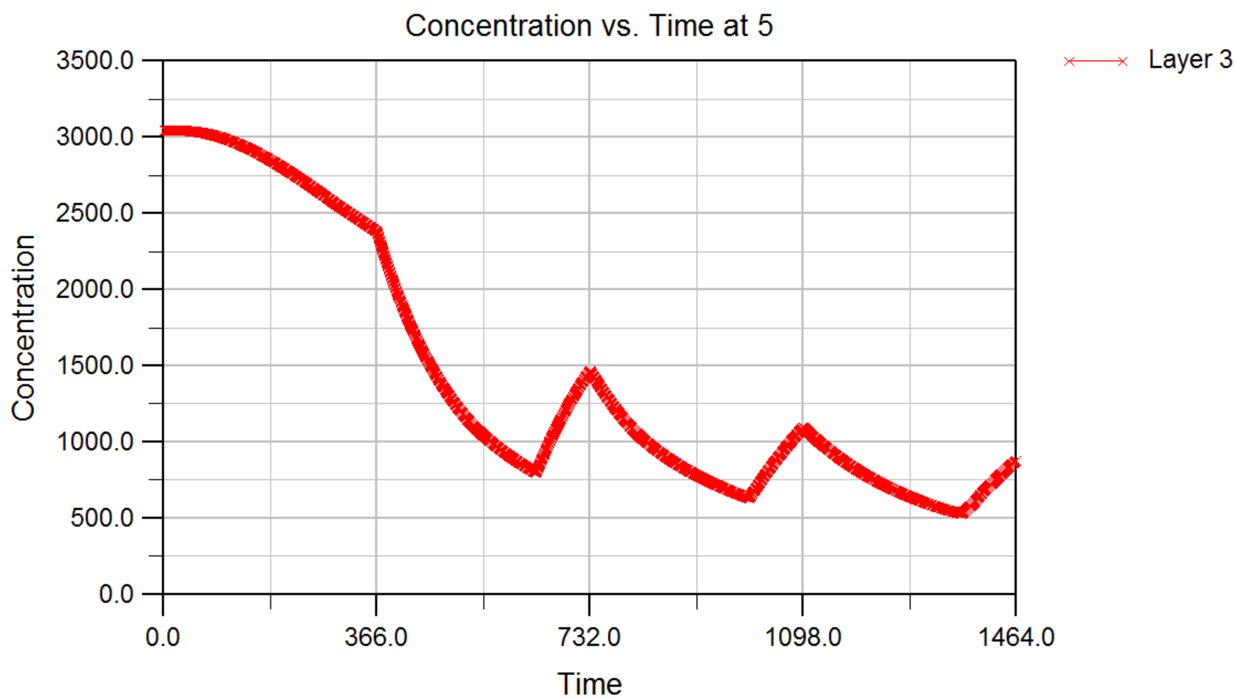


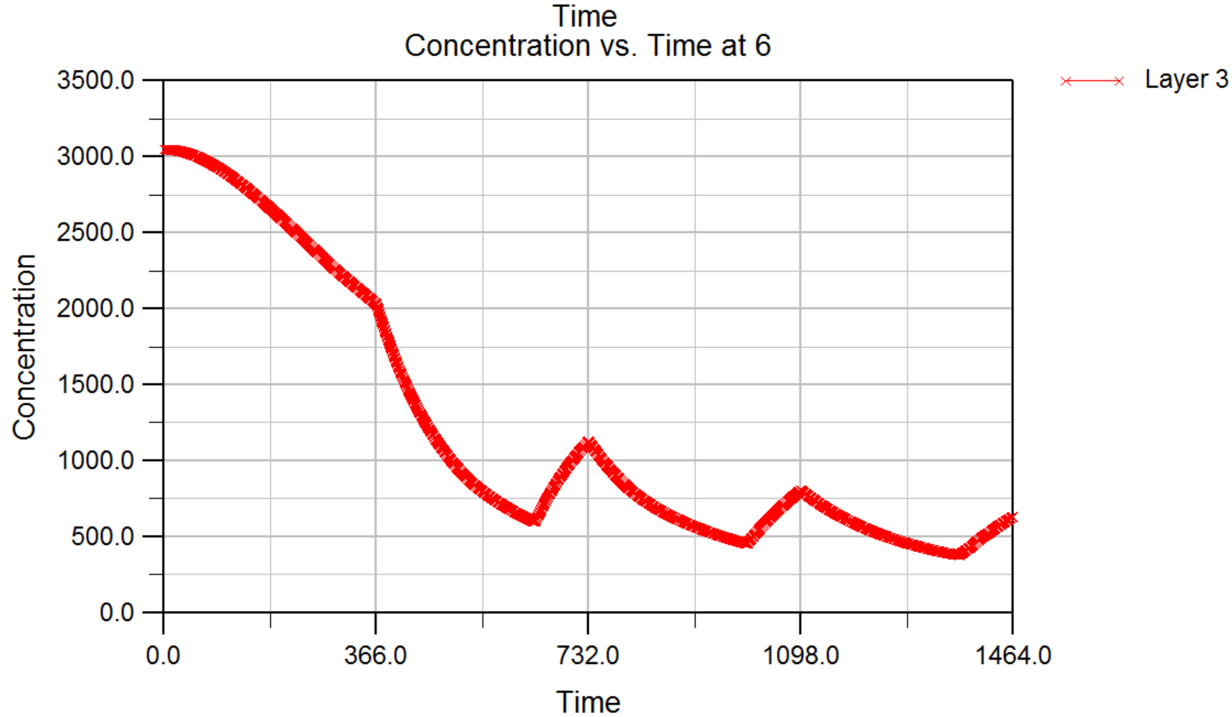

Concentration vs. Time at 1
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time

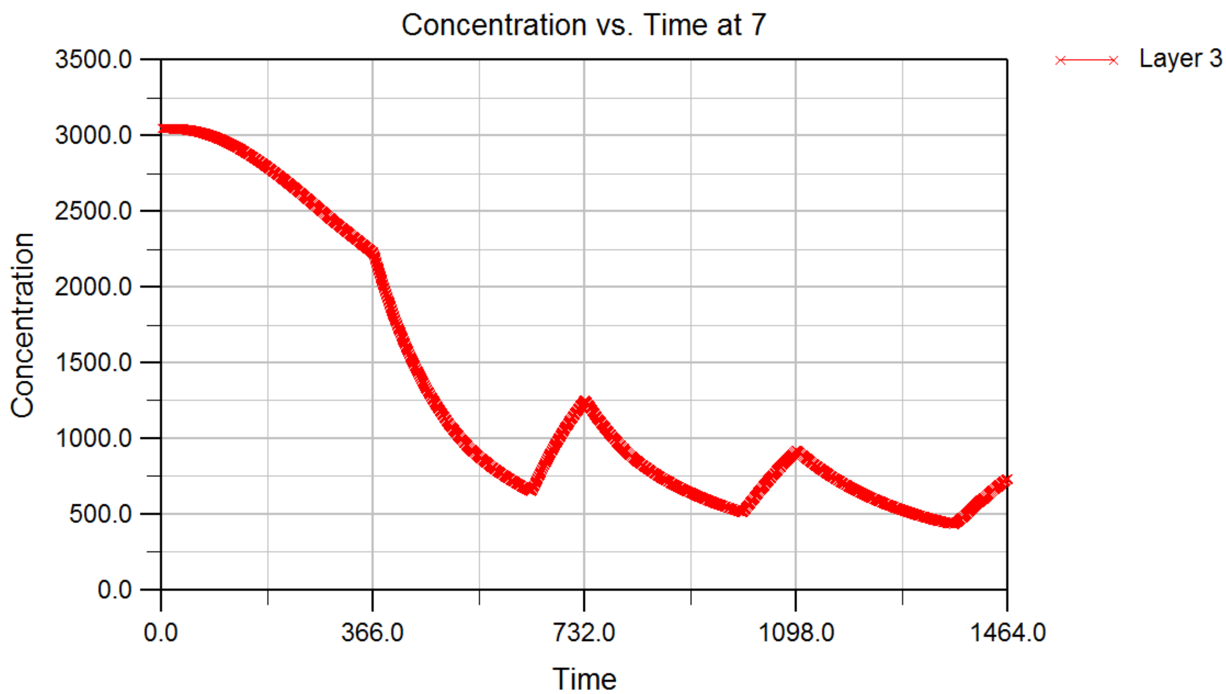

Concentration vs. Time at 2
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time

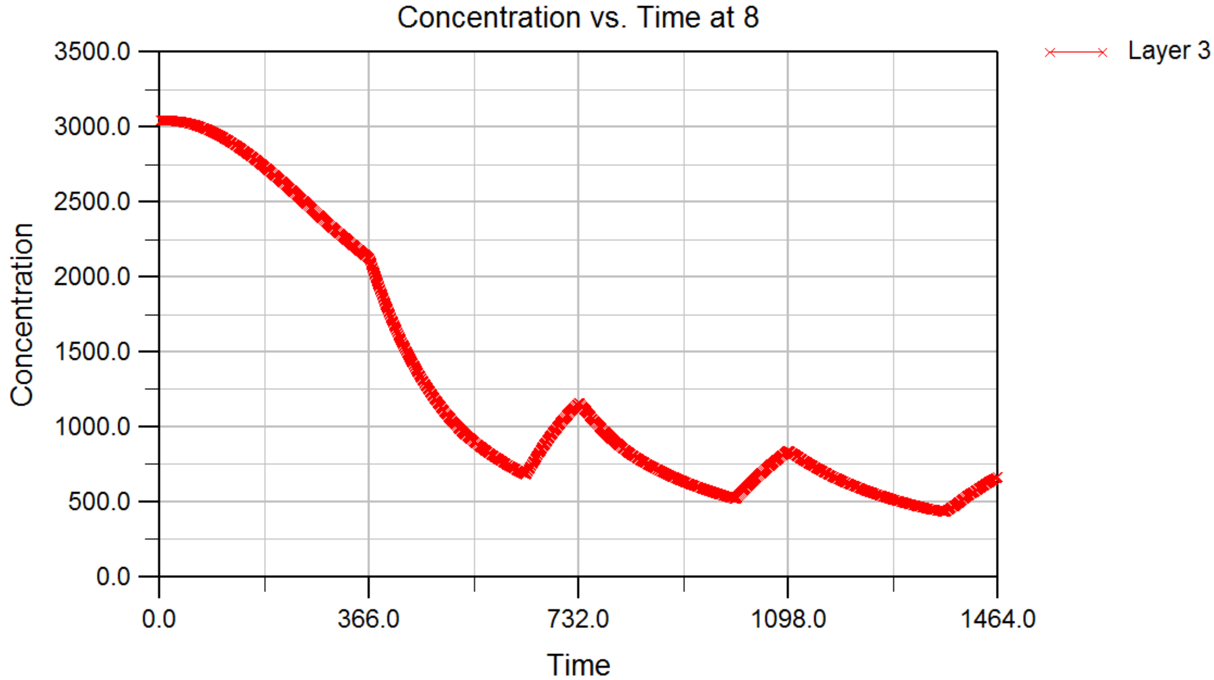

Concentration vs. Time at 3
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time


Concentration vs. Time at 4
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time


Concentration vs. Time at 5
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time


Concentration vs. Time at 6
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time


Concentration vs. Time at 7
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time


Concentration vs. Time at 8
Layer 3
Concentration
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.0
366.0
732.0
1098.0
1464.0
Time

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